

**Exploration of Robotic-Wheel Technology for Enhanced Urban Mobility and City
Scale Omni-Directional Personal Transportation.**

by

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S.B. Management Science, Massachusetts Institute of Technology, 2005

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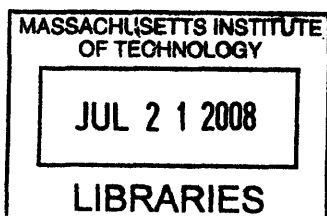
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Abstract

Mobility is traditionally thought of as freedom to access more goods and services. However, in my view, mobility is also largely about personal freedom, i.e., the ability to exceed one's physical limitations, in essence, to become "more than human" in physical capabilities.

This thesis explores novel designs for omni-directional motion in a mobility scooter, car and bus with the aim of increasing personal mobility and freedom. What links these designs is the use of split active caster wheel robot technology.

In the first section, societal and technological impacts of omni-directional motion in the city are examined. The second section of the thesis presents built and rendered prototypes of these three designs. The third and final section, evaluates implementation issues including robotic controls and an algorithm necessary for real world omni-directional mobility.

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1 Introduction

This thesis examines three modes of urban omni-directional mobility through the digital design exploration of a scooter, automobile, and bus using active and split-active caster wheel robot technology to guide the design process. These designs explore the potential for omni-directional mobility within the existing infrastructure of the contemporary city, and examine possible solutions for omni-directional mobility in the city of the future. The designs are evaluated by rapid prototyping four physical models of omni-directional mobility: a full scale split-active caster wheel robot, two quarter scale omni-directional vehicles each with three active caster wheel robots, and a quarter scale three wheel split-active caster omni-directional mobility-scooter. The steering geometry and control algorithm for four-wheel active caster omni-directional motion is outlined, looking at intra- and inter- vehicle robot wheel communication and the trade-offs between global- and user-centered vehicle control. The goal of the design process and fabrication is to explore the validity of city scale omni-directional mobility vehicles.

1.1 Evolution and Mobility

According to Michael Gleich, science journalist and author of the book *Mobility - Mankind on the Move*, the “Big Bang” set the universe in motion – rather “into a state of continual unrest” – and *mobility* became the key to the successful evolution of life on earth. An imbalance in the distributions of natural resources – such as water, food and breeding grounds – along with cosmic climate changes over space and time, cause shortages and surpluses that affect the evolution of life. In order to propagate and survive, living beings need to move toward vital resources and away from threatening events. Mobile beings, to this extent, are emancipated from the whims of nature and free from the finite resources of a fixed environment.

Amidst this universal unrest, evolution produces a group of mobile generalists who finds success in both expedited motion and slow settlement. In search of surplus, living beings that move the quickest have the greatest opportunities to evolve. In light of shortage, conservation of energy necessitates the deliberation of motion. Both strategies compete for scarce resources but sometimes they can cooperate to the benefit of each other.

As mobile beings, humans have progressively freed themselves from the restrictions of the inanimate world by learning to both adapt to and change their surroundings. The development of numerous tools and mobility devices are evidence of mankind’s determination to overcome its natural limitations. Thus, humanities ingenuity finds its extension in the cultural and technological advancement of its civilizations.

Nomads and settlers exemplify humanity’s own evolution through motion and settlement. The former continually traveled towards greener pastures; the latter established rooted civilizations. Herdsman, with a habitat marked by shortage, sustained life by moving to new grazing areas while living off the surplus of the herd. Agrarians settled in fixed locations, created surplus by tending the land, sowing and reaping their harvest. Together these nomads and settlers traveled to the city, creating a center for commerce and culture.

The necessity for trade between cities, villages, regions, or peoples results from the fact that ore, timber, amber, fruits, salt, or water are not deposited through space according to the laws of physics and geology, and not according to the principles of fairness. In one place there are surpluses, in another place there are shortages. A difference, or rather, differences occur. Trade and freight move along the imaginary line of demand. Differences provoke mobility.

Parallels can perhaps be drawn between the agrarian settler and the traveling trader to the modern city dweller and suburban commuter.

1.2 City Scale Mobility

Mobility on the city scale demands the ability to access and navigate any and all combinations of urban space, time, information, and psyche. To increase the sensation of being mobile, one must take advantage of the opportunity to engage with and exchange with diverse environments. The city is an invention which maximizes the exchange of goods, services, culture, and human interaction while minimizing travel for such pleasures. Therefore the function and purpose of the city are examined in order to make recommendations on the future of urban mobility with regards to omni-directional motion. A brief chronological history of the western development of the organized city is presented with respect to urban design and mobility. Next the fabric and image of the city is discussed with a focus on transportation, nodes and pathways. Finally issues of sustainable mobility are addressed which conclude with the design principles for city-scale mobility.

Through the years, mobility and transportation have contributed to the success of urban life and thus have influenced the structure and development of the city. The many royal cities of the Roman Empire took the cruciform shape using two major streets that formed the arteries of the city from north to south and east to west, along which all of the royal buildings were placed. A haphazard development of streets and alleyways acted as the veins and capillaries that completed the circulation between the four quadrants out to the city walls. As the royal cities grew new walls were built concentrically around existing walls and the major arteries extended further and fed a greater area leading back to the heart of the city. As these arteries extended from the city center to more distant boundaries, new nodes and districts developed along with a maze of connective pathways. Even in the pre-automobile city, these nodes of interaction, such as churches and city squares created the “intense and active meeting places for commerce, the exchange of ideas, worship, and recreation” (Safdie, 12) which defined city life.

The modern city is largely a product of attempts to adapt the historic city to the needs of 19th century industrialization. During the turn of the century changing transportation and density needs were addressed with the automobile, the high rise complex, and decentralization as existing urban systems and linearly increasing hierarchy of scale were not viable solutions. The utopian visions of the modern city and the automobile include

the multi-level transportation networks drawn by Harvey Wiley Corbett, the dispersed Broadacre City of Frank Lloyd Wright, and the concentration of open space high-rise towers, wide avenues and sheltered parking structures envisioned by Le Corbusier. Yet when implemented, the utopian ideal of the modern city created a network of endless parking lots, entangled highways and disconnected high-rises leaving indistinguishable in between space that lacked the urban connectivity crucial to the vitality of the city. In particular, the designers of the modern city overlooked the pedestrian and one of the original benefits of urbanity, to facilitate interaction among people.

City development today has reached the mega scale, where airports, shopping malls, office buildings, hospitals and apartment complexes have become cities within themselves. These mega-complexes accommodate the flow and order of tens of thousands of people, where the major corridors and hallways become interior streets and alleys. This trend toward the mega scale city is an effect of a population explosion, economies of scale, optimization of organizations, systems efficiency, and the structure of society.

It is not mass culture that is being displayed, but the uncontrolled, rampant emergence of a post-industrial consumer economy gone mad – pouring into cities in every part of the world, growing at an enormous rate, and consuming limited, precious resources. (Safdie, M. p 91, 1997)

The result is a windowless environment of undifferentiated workspace, processed air, artificial light and repetitive structure. In this world, it is easy for the citizen of the mega city to feel small, anonymous and insignificant. The scale reaches such a dimension that citizens are either forced to move further away from or possibly become lost in the dense, repetitive and ever-expanding core.

1.3 Sustainable Mobility

The racing development of ubiquitous digital technologies, especially low-cost wireless and distributed devices, will certainly have paradigm-shifting impacts on social networks and the nature of social interaction and exchange. The evolution of these social norms will be entwined with the transformation of cityscapes and transportation. Any exploration of potential transportation designs must consider not only the impacts of telecommunications technology on the designs themselves, but also the impact on social structures and networks which in turn influences the demands on transportation solutions. Indeed, the impacts of all these new technologies on social structures, communities and equity and the environment must be considered.

Just as designers moved away from the utopian city, green design and smart growth are being implemented to balance the humanistic needs ignored by the mega city. These principles aim to fulfill the concept of sustainable development, Fig. 1.1.

Focus	Typical Definition	Representatives
Maintenance of natural capital stock	Social development under the condition that the natural capital stock (soil and water quality, biomass, absorption of wastes) does not deteriorate.	Pearce et al., 1988 Stephan, 1990 Ayres, 1994
Justice between generations	Development that satisfies the needs of the current generation without jeopardizing the ability of future generations to fulfill their needs.	Pearce, 1987 Enquete-Commission, 1994 Brundtland Report, 1987 Sustainable Netherlands, 1992 Wuppertal-Institute, 1996
Constant or increasing wealth	An optimal resource and environmental management demands sustained economic growth under the condition of maintaining the services and quality of natural resources.	Brundtland Report, 1987 Barbier, 1989 International Chamber of Trade and Commerce, 1991

Fig. 1 Definition of Sustainable Development

Sustainable mobility must thus address three issues: the efficient use of limited resources; a transition toward the use of renewable resources; and the adoption of new concepts for mobility services. Improvements in these areas include the efficient production and use of fossil fuels, advances in internal combustion systems, continued innovations in vehicle production processes and materials, Fig. 1.2.

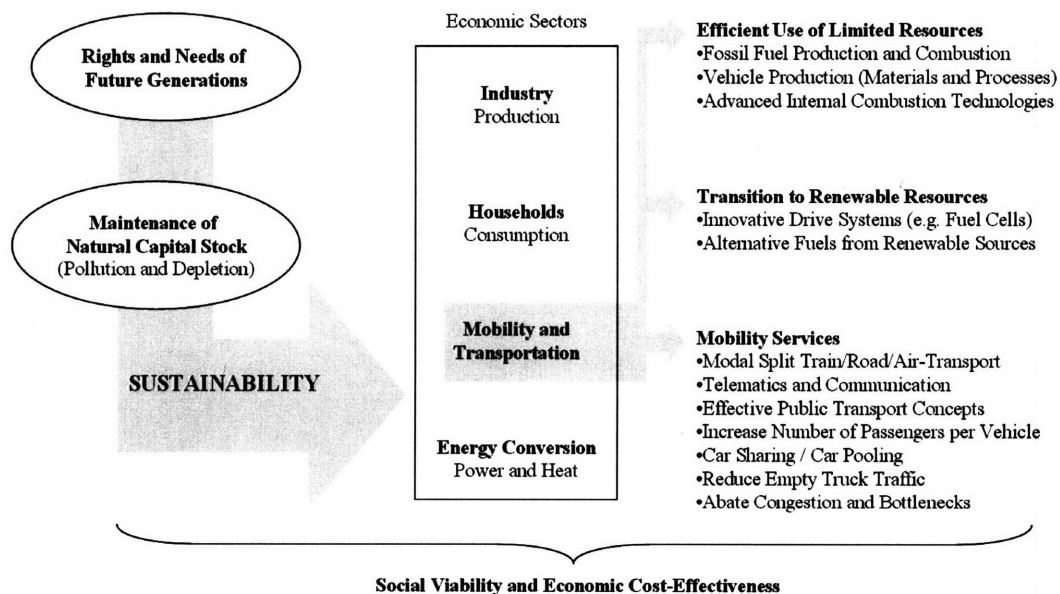


Fig. 1.2 Deriving Sustainable Mobility in a Target System

A plane may maximize distance traveled over time, but provides a limited choice of original and destination environments. On the other hand, optimal urban mobility aims to minimize bottlenecks and traffic for a wide selection of origins and destinations and increase the ability to interact with the environment along the route, hence valuing the journey as much as the destination.

The narrow selection of vehicle choices available today has saturated the traffic bandwidth of the existing infrastructure, while also placing further demand for the same kind of infrastructure. “As the car shaped the city, so the city itself is now shaped to require cars.” (Safdie, 127). To achieve a diversification of transportation solutions, new vehicles must enable improved utilization of current infrastructure while being adaptable to future and novel urban developments. Without diversification, city design may be forced to cater to a single transportation solution that sacrifices its most precious resource, land, for increased bandwidth.

Considering the complexity of intertwined factors that will drive the evolution of technology and its impact on the city, five principles have been raised to guide sustainable solutions: dematerialization, demobilization, mass customization, intelligent operation and soft transformation (Mitchell, E-topia).

The minimizing of physical materials or dematerialization, buildings as well as infrastructure, can be hastened by replacing the mechanical and tangible with digital functionality. Demobilization would call for less unnecessary transportation and cargo. Mass customization demands greater choice with simple mass solutions, as could be achieved by the wheel robot and other digitally controlled, modular and interchangeable components. The wheel robot fits into different design solutions and allows for changing characteristics of the car and dynamics.

It is clear that mobility on demand, through vehicle routing and vehicle sharing, will lend itself to dematerialization and demobilization, by reducing the overall number of cars and road space, replaced by digitized scheduling, booking and access, reducing the need for rental centers and parking. At the same time, mobility on demand benefits to demobilization and mass customization go hand in hand with intelligent operation as distributed rental locations and better choice in rental scheduling and vehicle type reduces the overall number of cars on the road, aids in both integrating mixed modes of transportation and the ability to optimize resource usage.

Intelligent operation can further be incorporated into these designs as vehicle interfaces become more intuitive, and background devices make decisions for the user. Intelligent devices can further aid in logistics and prevent mistakes, such as global control and inter-vehicle communication to guide traffic flow, or a yaw sensor to control omni-directional vehicle maneuvers that exceed limits at a given vehicle speed.

Shrinking vehicle size, shared ownership models and other forms of flexibility and personalization are among the alternatives. Global-centered traffic coordination could

enable the optimal use of technologies such as omni-directional vehicles in an environment of diverse transportation alternatives, while offering the capability of navigating future mixed-use roads that break from the traditional traffic grid.

2 Omni Directional Wheel Robot Technology Design Issues

2.1 Physical Limits of Omni-Directional Motion and Devices

The term Omni-directional is used to describe the ability to move instantaneously in any direction from any configuration. Omni-directional robots or automated vehicles can perform important tasks in environments congested with static and/or dynamic obstacles and narrow aisles (ref. Yu, Dubowsky, Skwersky). Most studies in omni-directional motion have been in controlled environments where the devices were designed for low speed robot applications and tested on level-planes. Real world benefits of omni-directional motion devices have been proven in office buildings, warehouse aisles, factory floors, aircraft carrier top decks and hospital corridors. As of yet, the dynamics and stability issues of omni-directional motion have not been fully explored in high speed applications or urban use environments. The limits of omni-directional motion like the motion of any vehicle are dependent on changes in velocity, in relation to the vehicle center of gravity, the configuration of the vehicle foot print, and the friction at the contact patch of the wheels. With the appropriate design consideration, multi-speed omni-directional motion may be accomplished on the urban scale.

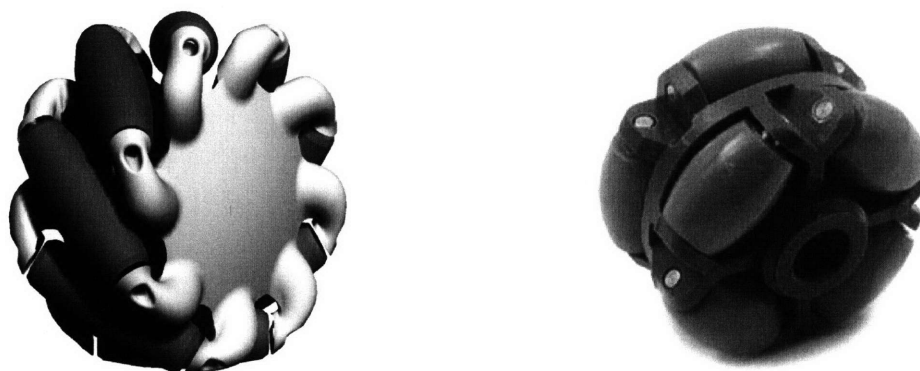


Fig. 2.1 Omni-Directional Specialty Wheels; a) Mecanum, b) Double Universal

Completely omni-directional devices, which follow non-continuous curved paths, are categorized into two groups: those that utilize special wheel designs and those that use conventional wheels with caster steering. The majority of the devices categorized as specialty wheels achieve omni-directional motion by allowing traction in one direction and passive motion in the other. The most recognized specialty wheels, the Mecanum and universal wheel, Fig. 2.1, utilize rollers uniquely mounted on their periphery to create a desired traction and slip patterns. Other omni-directional specialty wheel mechanisms include the VUTON, Orthogonal wheel, and the Ball/Spherical wheel. These specialty

wheel configurations often have limited load capacity and poor ground clearance depending on the size of the roller pins and the diameter of the passive rollers respectively. The non-continuous curvature of some of the specialty wheels can also cause unwanted vibrations and allow dirt to be trapped in between the rollers of the wheels. The dynamics of the passive rollers are often unaccounted for, resulting in limited accuracy of motion and poor dead-reckoning of position and orientation. The complex nature of specialty wheel designs makes them less amenable for use in high payloads applications and environments with exposure to dirt or variegated surfaces.

Omni-directional devices that use conventional wheels with caster steering include the active offset caster and the split active offset caster designs. Both designs benefit from the inherent simplicity of a conventional wheel and altogether avoid a number of the difficulties encountered by specialty wheels. Some of the advantages that a conventional wheel with caster steering possesses are its mechanical simplicity, greater tolerance to irregularities in driving surface, and high load capacity. Also, the continuous curved surface of a conventional wheel maintains constant contact with the ground which minimizes vibrations during rotation and provides a known point of contact for more precise control of vehicle position and orientation. The dynamics of a conventional wheel can be accurately modeled since there are no unmeasured bodies like the passive rollers of the specialty wheels. This thesis explores in depth, the conventional wheel with a number of active caster steering solutions and vehicle configurations.

The instability associated with omni-directional motion at high speeds is related to the changes in footprint orientation relative to the direction of motion and the changes in velocity as an omni-directional maneuver is performed. Rapid changes in velocity effect vehicle stability dependent on the foot print orientation, and the resultant force distribution. Changes in footprint orientation also effect the moments about which the forces are balanced during rapid changes in velocity.

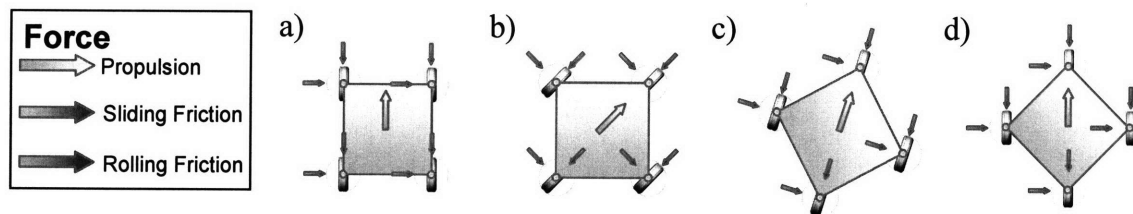


Fig. 2.1: Force balance of 4 wheel omni-caster vehicle in a series of maneuvers:
a) forward trans, b) 45 degree trans, c) rotation-translation, d) forward, 45 degrees.

For the case of the omni caster design, the resultant forces from changes in velocity are counteracted by the rolling friction and sliding friction, Fig. 2.1. The opposing forces intersect perpendicularly with each other such that their resultant vector balance the forces created by changes in velocity. Therefore as the resultant force of rolling and sliding friction balance the forces of turning, the moments on a vehicle change as the wheel footprint geometries rotate about the path of motion.

a)

b)

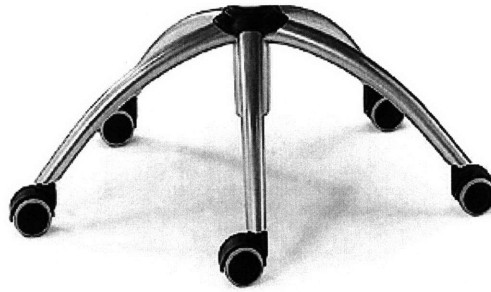
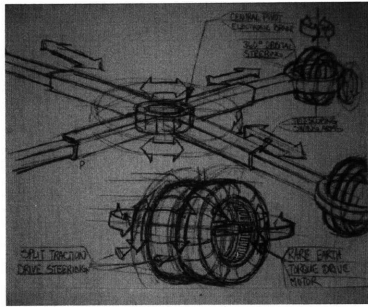


Fig. 2.2: a) Dynamic SAC Chassis, b) Lower Section Rolling Office Chair

Balancing the moments about each wheel is crucial to the dynamic stability of the vehicles. For vehicles utilizing active caster technology, a dynamic chassis is a possible solution for high speed applications of omni-directional motion, where the center of gravity and the vehicle foot print are changed in real time to balance the active moments, Fig. 2.2a. Another solution to balance the changing moments is to create controlled slip patterns in omni-directional devices, which allow the vehicle to slip instead of flip during extreme maneuvers. A spherical wheel is a great example of the slip before flip strategy, where the slip is equal in any direction. These extreme maneuvers can be managed by gyroscopic sensing of a vehicle's climb, dive and yaw. It is also important to create footprint geometries which lie equidistant about the same circle. As the number of equidistant contact points about a circle increase, the stability of the vehicle increases during rotational and translational turning, i.e. more wheels on a rolling office chair make the chair increasingly stable, Fig. 1.2b. All of these strategies, dynamic chassis, controlled slip and increased number of equidistant contact points about a circle, in combination or in part are important to the success of high speed city scale omni-directional motion.

2.2 Active Caster and Split-Active Caster Technology

Under high load and tolerances, there are advantages and disadvantages to both the active caster and split active caster technologies. One concern with active caster wheels is the high rubbing friction experienced when rotating about a vertical axis, which is especially pronounced when stationary. This friction results in high wear due to wheel scrubbing, increased power consumption and a loss of steering precision. Conventional caster wheels tend to avoid this problem by rolling while rotating. The torque required to overcome scrubbing may be 10 times that required to overcome rolling friction (ref. Yu, Dub, Sw). A split dual wheel design, as seen in aircraft landing gear, is an alternative that significantly reduces these scrubbing effects, Fig. 2.31a-c. During stationary steering, the independent wheels of a split caster may roll while they rotate about a vertical axis. Further, a dual split active caster can be implemented with a pair of independent drive motors that enable traction steering about the caster pivot. Thus the dual split active caster design eliminates the need for a dedicated steering motor which translates into a direct increase of the drive train power to weight ratio.

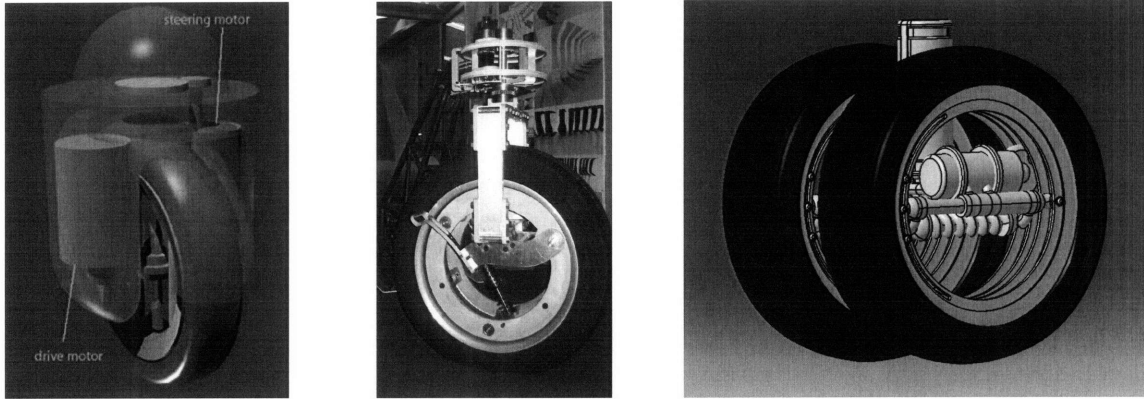


Fig. 2.3: Active Caster Split Active Caster: a) AC, b) Zero Car – AC, c) SAC.

In order to achieve omni-directional motion, an ideal caster design would incorporate a forward offset between the steering pivot point and the vertical center of the wheel. The series of active caster wheels in Fig. 2.4 – conventional, sideways offset, forward offset steered, and dual split forward offset steered – illustrates the corresponding velocity distribution for three unique steering pivot point geometries. Each active caster wheel has two actuators individually dedicated to the tasks of steering and driving.

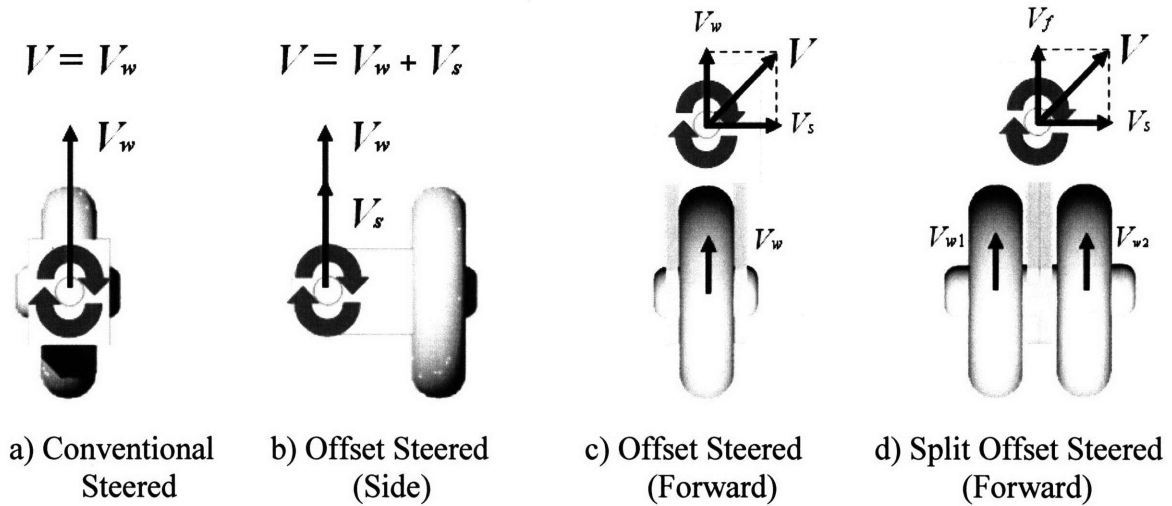


Fig. 2.4, Series of Active Caster Wheels

For the conventionally steered caster, Fig. 2.4 (a), the steering pivot point is centered with the vertical middle of the wheel such that the motions of the steering and drive actuators are mechanically decoupled from each other. In this configuration, the steering actuator can only rotate the wheel concentrically about the steering shaft and is unable to translate the pivot point during a steering operation. Thus the caster wheel pivot point can only move in one direction at each instance of the wheel's traveling velocity V_w and is therefore not omni-directional by nature.

An offset steered caster wheel utilizes a steering configuration where the steering pivot point is remotely off center from the vertical middle of the wheel. The offset geometry of a remote pivot steering configurations creates a coupled interaction between the translational motion of the steering pivot point and the independent actuation of the steering and drive motors. This coupled interaction is important for the instantaneous translation of the steering pivot point in an omni-directional manner.

In the case of the side offset steered caster wheel, Fig. 2.4 (b), the torque applied by the steering actuator can move the steering pivot about the wheel's point of contact with a velocity V_s . Yet due to the directional coincidence of the steering velocity V_s and the drive wheel velocity V_w , the steering pivot point cannot be translated immediately in any direction at any given time. Thus the side offset steered caster wheel is not a true omni-directional solution.

For the forward offset steered caster wheels, Fig. 2.4 (c), the directional velocity of the steering actuator V_s is always perpendicular to the directional velocity of the drive wheel V_w . Therefore, the steering pivot point can be moved arbitrarily in any direction by independently controlling the steering actuator angular velocity V_s and the angular velocity of the drive wheel V_w . The forward offset steered caster wheel therefore is an omni-directional solution.

Finally in the case of the forward steered split caster wheels, Fig. 2.4 (d), the directional velocity of the wheel actuators V_{w1} , V_{w2} combine to create a resultant velocity V defined by a forward V_f and translational steering velocity V_s . Similar to forward offset steered caster wheel, the steering velocity V_s is perpendicular to the velocity of the drive wheel V_f therefore the steering pivot point can be moved omni-directionally by independently controlling the angular velocity of V_{w1} , V_{w2} . This omni-directional solution provides the most energy efficient means of caster steering.

2.3 Hub vs. Hub-less Split-Active Caster Wheel-Robot

The hub and hub-less caster wheel-robots are designed such that the mechanisms for propulsion, braking, suspension, omni-steering and vehicle intelligence are separated from the vehicle and integrated into the volume allotted by the wheel. The integration of these components with the wheel raises concerns about packaging, form factor, and the dynamic distribution of mass. A well designed wheel-robot will minimize rotational and un-sprung mass in order to reduce the necessary magnitude of damping for the moving components. A comparison of the hub and hub-less split-active caster designs will evaluate the complexities of the component integration of two wheel-robots and their unique approaches to reduce un-sprung mass.

The hub split-active caster wheel-robot drive units implement a four-bar suspension linkage with an integrated transmission that provides power to the wheels and separates the drive motor from the un-sprung mass. The geometric symmetry of the four-bar linkage mechanically constrains the radial distance between the reduction gears of the motor output shaft and the wheel drive shaft. Here the wheel, disc brake and drive shaft are supported by two conventional ball bearings flanked by the dynamic transmission case of the four-bar linkage, Fig. 2.4.

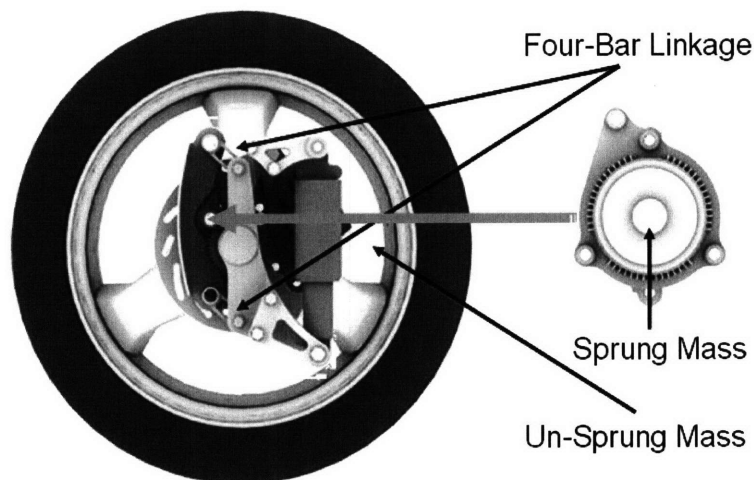


Fig. 2.4 Four-Bar Linkage Dynamic Transmission Case

The exploded view of the hub split-active caster wheel-robot drive unit, Fig. 2.5, illustrates the division of the integrated components and the separation of sprung and un-sprung mass. To the right of the dashed line are the components – rim, tire, disc brake, and drive shaft - that are considered the un-sprung and rotational mass of the drive unit. To the left of the dashed red line sits the drive motor that is rigidly connected to the steering fork, which is therefore considered a portion of the sprung mass.

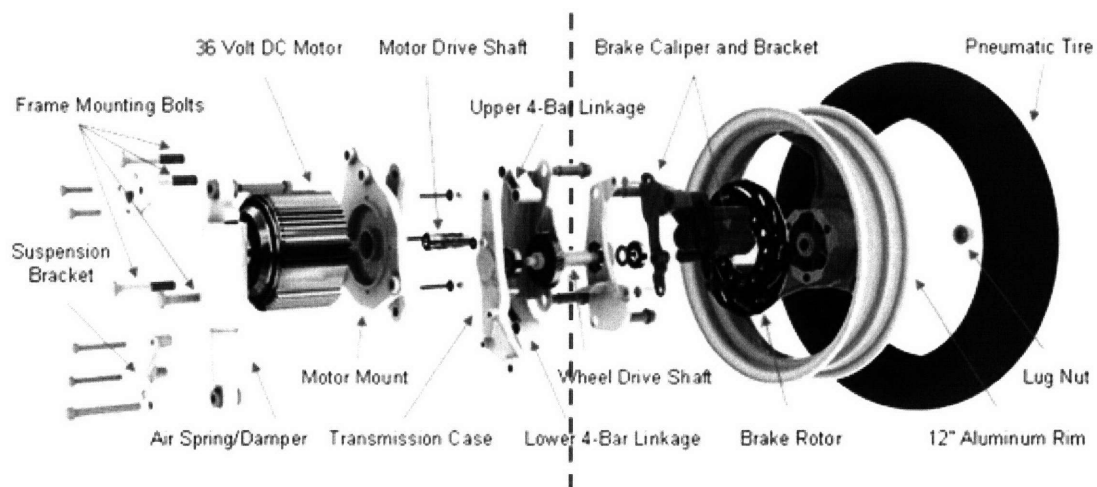


Fig. 2.5 Exploded View of the Hub Split-Active Caster Wheel-Robot Drive Unit

The assembled hub split-active caster wheel-robot drive unit and its connection to the steering are illustrated below, Fig. 2.6.

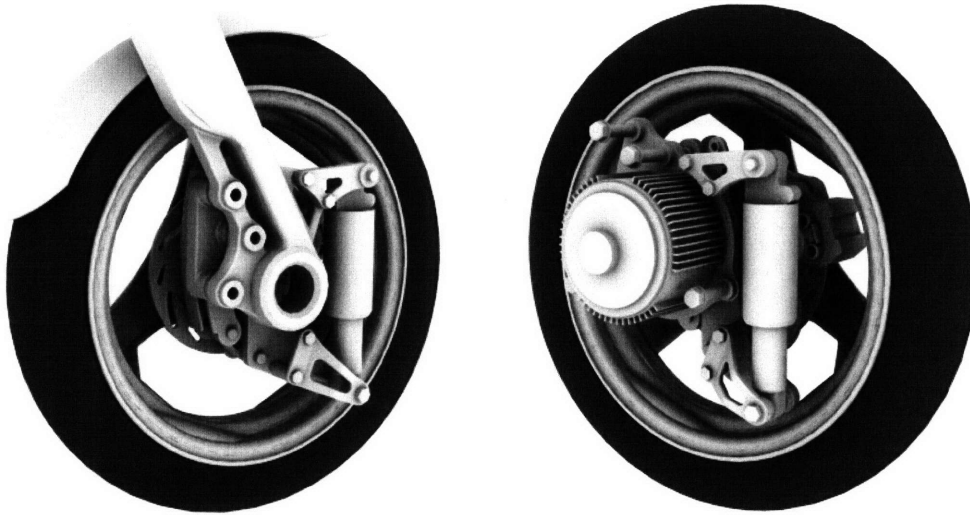


Fig. 2.6 Wheel-Robot: Assembled Drive Unit and Connection to Steering Fork

Mounting the dual drive units to the steering fork completes the hub split-active caster wheel-robot assembly, Fig. 2.7. Since the steering fork has an angular velocity associated with the velocity differential of the drive wheels, the dual wheel-robot drive units are classified as a portion of the rotational steering mass of the hub split-active caster wheel-robot. Therefore it may be necessary to actively brake the caster steering shaft in order to counter balance the rotational inertia of the fork and the dual drive units.

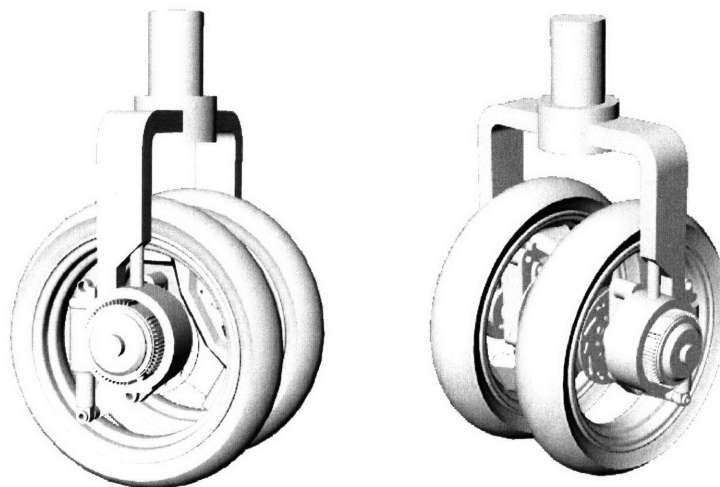


Fig. 2.7 Hub Split-Active Caster Wheel-Robot Assembly

The horizontal-pivot hub-less split-active caster wheel-robot implements a linearly compressed swing arm linkage with a drive train power transfer located at the suspension pivot point. The swing arm is geometrically constrained such that the loaded suspension linkage is compressed by shortening the chord length, in blue, between the drive train pivot, in red, and the free pivot that roll along the internal ring gear, in green, shown in Fig. 2.8.

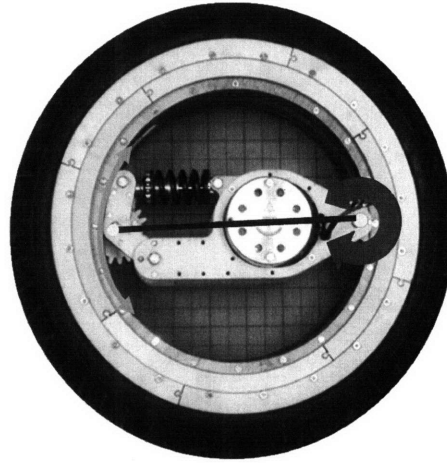
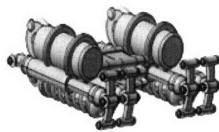
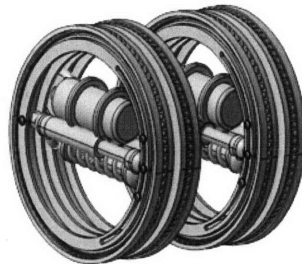


Fig. 2.8 Horizontal-Pivot Hub-Less Drive Unit Suspension Geometry

In this design the motor is located on the swing arm and is thus isolated from the un-sprung mass, Fig 2.9 a. The rim and ring gear are supported by two large diameter thin section tapered roller bearings and thus rotate freely about the internal bearing casing and integrated swing arm, Fig. 2. b. In the fully assembled hub-less split-active wheel robot, the amount of un-sprung mass is approximated by the outer rim, tire and bearing casing, Fig. 2.9 c .



a.)



b.)



c.)

Fig. 2.9 Horizontal-Pivot Hub-Less Split-Active Caster Wheel-Robot Assembly

Further illustration of the hub-less split-active wheel robot are shown below where the swing arm is defined by the orange components, the dual drive motors are shown in red, the coil over suspension is colored in blue, and the large diameter bearing and internal ring gears are visible in the transparency of the rim, Fig 2.10 a. The entire assembly is attached to the chassis via a steering shaft and is considered a part of the rotational steering mass, Fig 2.10 b.

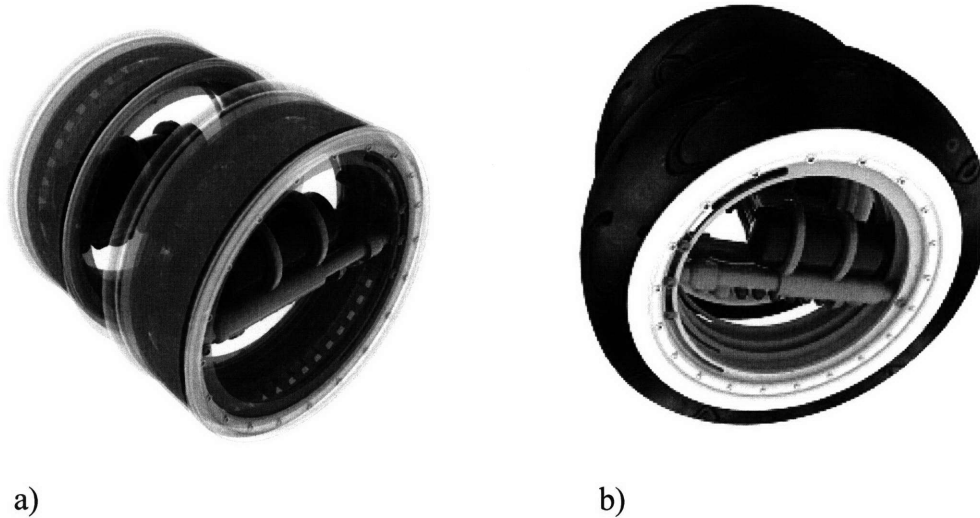


Fig. 2.10 Hub-Less Split-Active Caster Wheel-Robot with Highlighted Components

The full scale prototype was built using $\frac{1}{4}$ inch laser cut plywood layer and fastened by 8-32 threaded rod and laminated with wood glue, Fig 2.11 a. A set of four, 14.5 inch inside diameter thin section tapered roller bearing, donated by Timken, were used to support the rotation of the outer rim and internal ring gear. The dual 48VDC ,1200 watt brush motors powered the individual drive units at 3000 with a 6:1 drive train reduction between the motor out put shaft and the and internal ring gear, Fig. 2.11 b. The dual independent 5-3/4 inch coil over adjustable suspension have a 1500 pounds per inch (LBS/IN) spring tension rating each. The swing arm was designed to support a quarter of the weight of a one ton vehicle with 4 inches of suspension travel. The dual 17 inch tires are 3.5 inches wide and together create a 10 inch wide assembled hub-less split-active wheel robot with a 3 inch connecting space between the drive units, Fig. 2.11c.

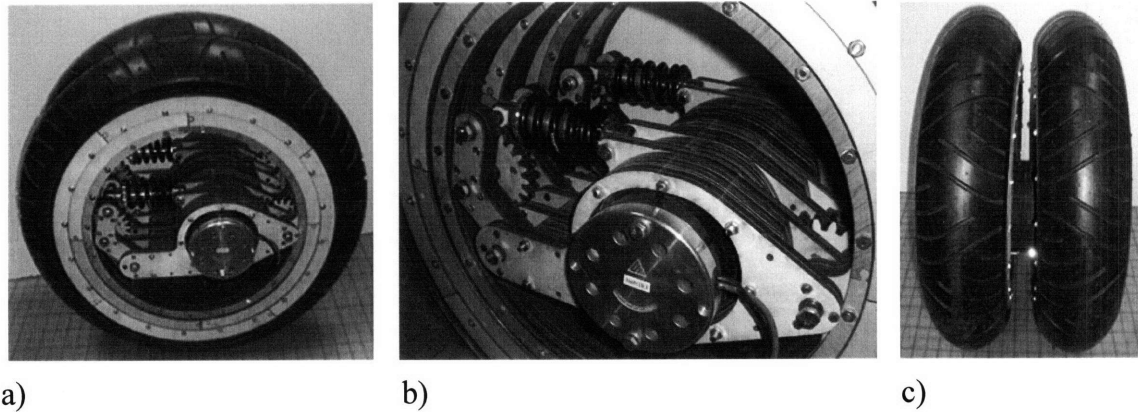


Fig. 2.11 Full Scale Assembled Hub-Less Split-Active Wheel Robot

The horizontal pivot hub-less split-active wheel robot can be abstracted one step further to allow for an integrated vertical climbing suspension and drive train. Here the horizontal pivot swing arm is replaced by a climbing unit which is constrained by vertically symmetric guides that allows the suspension to be linearly compressed between the chord length of dual pivot points. Intelligent management of the drive motors creates the possibility of an adjust ride height by independently controlling the angular velocity of dual drive trains about a common internal ring gear. An illustration of the vertical climb hub-less wheel-robot drive unit suspension travel can be seen below, Fig. 2.12.

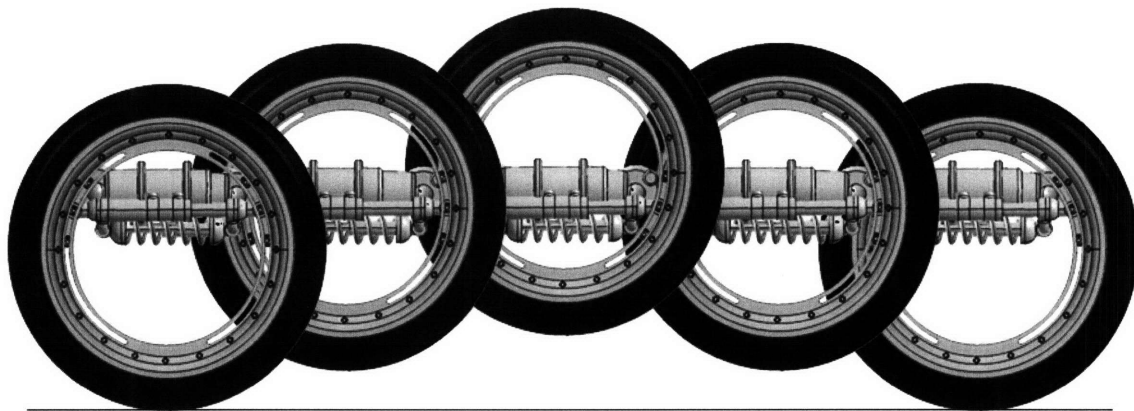


Fig. 2.12 Suspension Travel of the Vertical Climb Hub-Less Wheel-Robot

The two wheel designs both incorporate the benefits of dual independent drive motors while still isolating them from the un-sprung mass. The free internal wheel volume made available by using the hub-less design strategy allows for novel suspension geometries, which uses the curvature of the rim itself as a physical constraint for the compression of the suspension. The tradeoff complexities include additional weight and rolling friction from the large diameter roller bearings as well as a reduction in lateral stability due to the minimal contact of the suspension pivot points to the bearing casing. The four-bar linkage of the hub design strategy optimizes the suspension travel volume by minimizing the suspension linkages lengths while maximizing lateral stability by doubling the

number of suspension pivot contact points distribute over a parallelogram configuration. The hub design eliminates the need for the problematic large diameter bearings, simplifying the wheel-robot design and reducing cost. Over all, the Hub split-active caster wheel robot is most practical and economical design strategy.

2.4 Modular Connections

One of the major functions of the robot-wheel is to provide an exceedingly simple mechanical connection to the vehicle chassis with an integrated electrical connection to send both data and power to the wheel actuators and sensors. These modular connectors allow the wheel robots to easily plug-and-play into different vehicle platforms, or, alternatively, a single platform that can be dynamically reconfigured. These prototype connector designs explore the solution space of modular interfaces in search of a universal standard.

The first full prototype design, the Zero-Car, implements an overhead caster for 360-degrees of rotation which proved challenging to find an appropriate design and placement of steering components that could achieve sufficient torque to overcome the scrubbing friction of the wheel. The Zero-Car design implemented a steering fork similar to a bicycle with a head stock that was supported the steering shaft by a set of tapered roller bearings at each end of the neck pivot, Fig. 2.13 a. The modular interconnection was achieved by creating a threaded head stock that allowed the steering shaft and fork to drop out from under the neck of the chassis steering node, Fig. 2.13 b. This modular interface design caused some difficulty since one portion of the steering reduction gears were attached to the output shaft of the steering motor rigidly mounted to the chassis steering node, while the second set of reduction gears needed to be connected directly to the steering fork shaft in order to apply a steering torque to the wheels Fig. 2.13 c. Both the steering fork and the chassis node reduction gears need to vertically slide past each other, which created gear tolerance issues that resulted in losses in torque and steering accuracy.

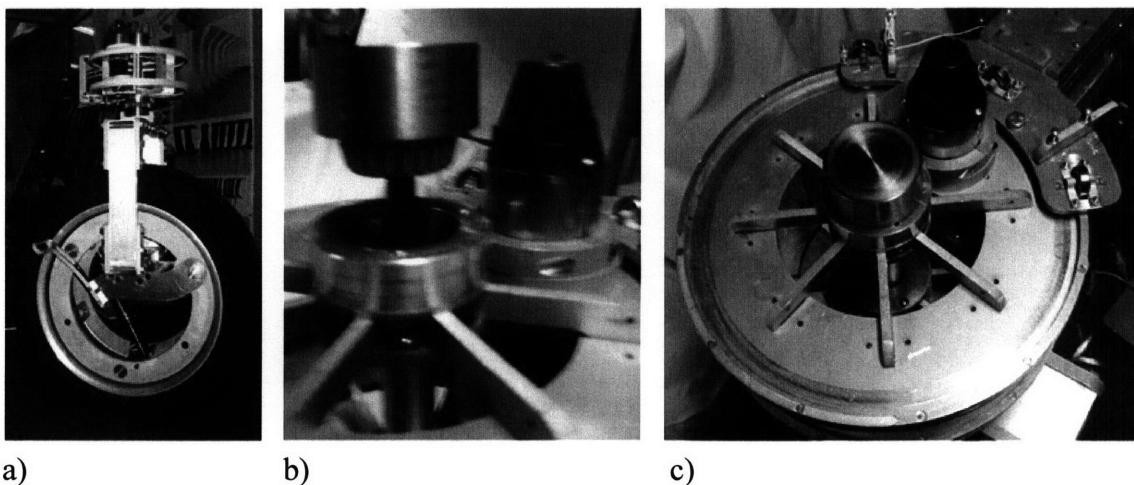


Fig. 2.13 Zero-Car Over-Head Caster Modular Steering Node

The second modular interface explored was the Waffle-Tech which was a steering node solution for a dynamically reconfigurable vehicle platform. Here a series of eight rotating blades are layered with staggered finger joints that interface with up to 4 waffle blocks, Fig 2.14 a. The blades fingers were designed to slide into the waffle blocks from both sides, to ensure a secure fit and even distribution of lateral forces, Fig. 2.14 b. The waffle blocks are a standardized universal connector between the chassis node and a number of plug and play add-ons, Fig. 2.14 c. The over all idea was that these node based interconnections would concentrically coincide with the overhead caster steering technology explored in the Zero-Car above, where the blades and turntable bearings also acted as slip rings for data and power transfer.

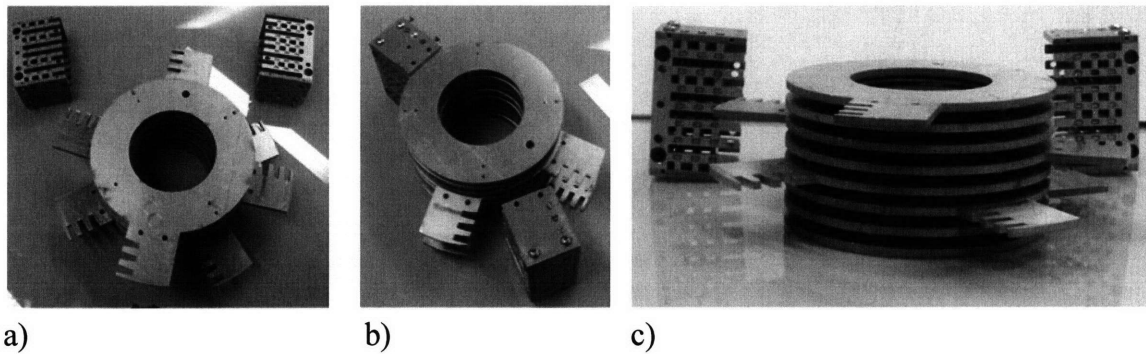


Fig. 2.14 Waffle-Tech Node Based Universal Connector for Plug and Play Add-Ons

The quick release designed for the split-active caster wheel-robot is a ball cam activated connector that mates with steering shaft, Fig. 2.15 a. The idea is borrowed from the quick release technology utilized to interchange pneumatic operated air tools that consist of a male and female connector which can concentrically rotate about each other while providing an air tight seal Fig. 2.15 b. The steering shaft has a similar design as the pneumatic tool nipple, providing the bearing races for the ball bearings that are mechanically integrated in the quick release cam mechanism Fig. 2.15 c.

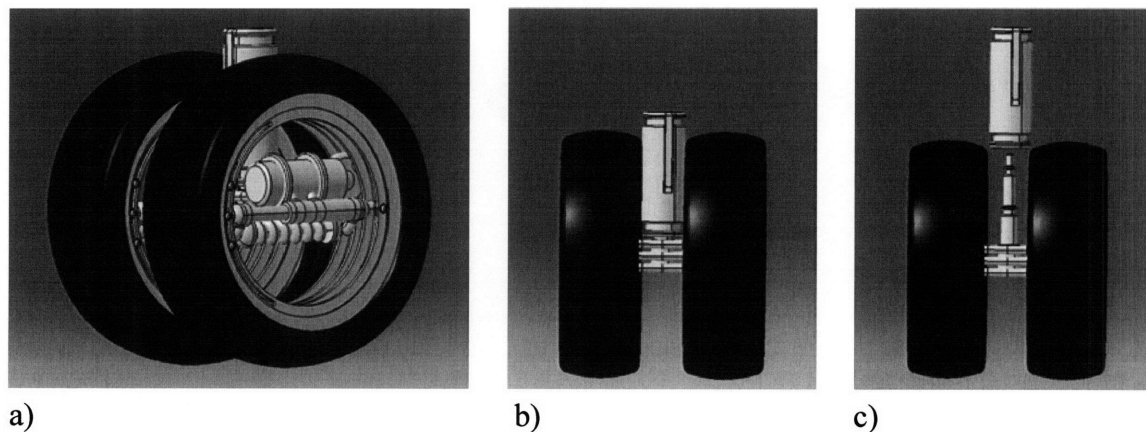


Fig. 2.15 Ball Cam Activated Quick Release Connector

The RoboScooter wheel robot technology explored multiple modular connections. One of the notable quick release strategies is based on the threaded knock-off technology used by Indy race cars. Here a large diameter fastener is used to secure the wheel-robot to the chassis, Fig. 2.16 a. This fastener is removed from the threaded wheel-robot motor mount, Fig. 2.16 b. The wheel-robot motor alignment and torque are addressed by a radially vertical key placed at the upper quadrant of the threaded motor mount, Fig. 2.16 c.

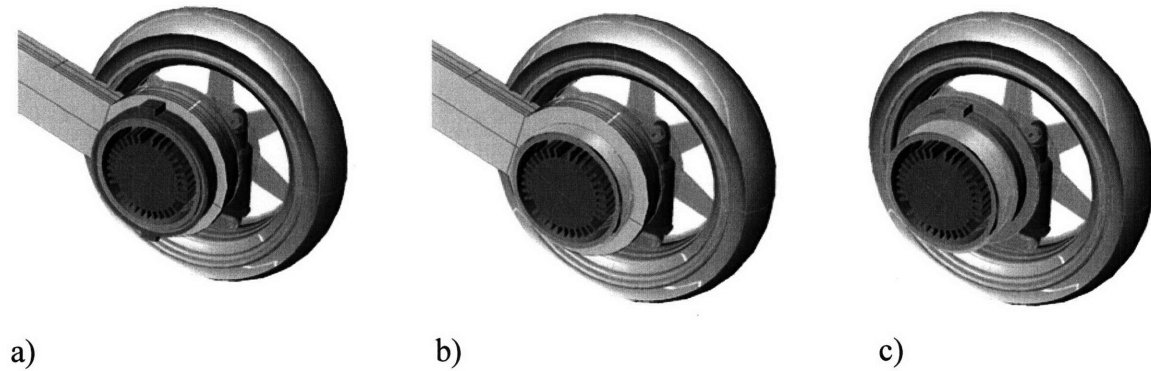


Fig. 2.16 Knock-Off Quick Release Large Dia. Fastener and Threaded Motor Mount

The final RoboScooter modular interconnection is based on a four bolt interface that can be used to mount the wheel-robot with both the front fork and rear chassis arm, Fig. 2.17 a, b. No intelligence or power is directly transferred by the modular interconnection of the vehicle. Rather the interconnection is purely mechanical and allows the exchange of wheel-robots, powered and un-powered, to change the driving characteristics of EV scooter – front wheel, rear wheel, and all wheel drive.

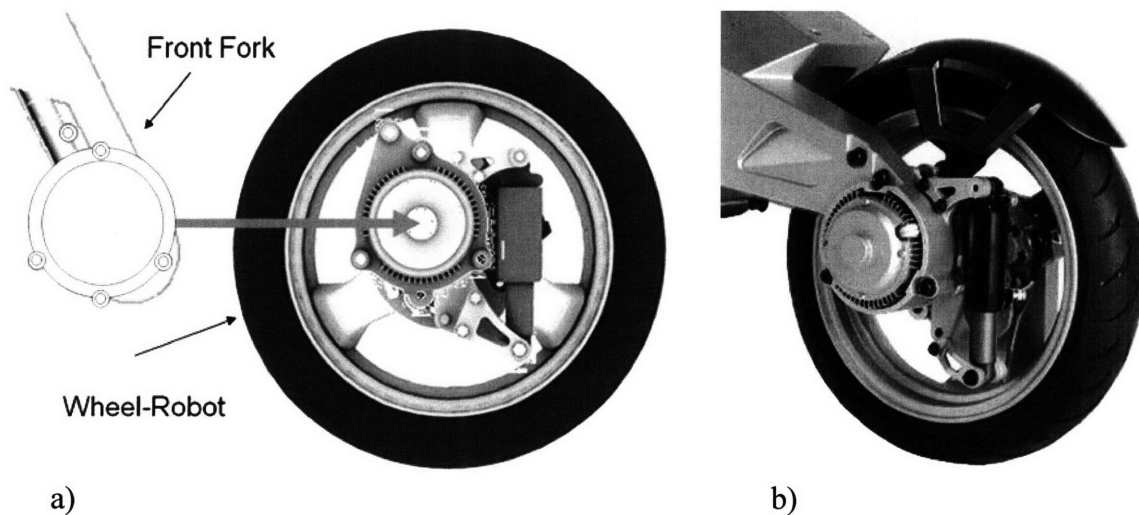


Fig. 2.17 RoboScooter Modular Interconnection with Universal 4 Bolt Interface

Finally, the first City-Car 4 wheel vehicle is based on a completely modular 80/20 extruded aluminum frame with side steered wheel-robot with two modules, the steering arm and the integrated drive unit. The steering arm has two distinct modular connection points, a 90 degree angled chassis mounting bracket and a pivoting drive unit mount, Fig. 2.18 a. The chassis mounting bracket attaches the steering arm to the 80/20 frame along two perpendicular faces using predrilled bolt patterns to fasten the steering module to the extruded channel Fig. 2.18 b. The side steered pivoting unit has two perpendicular surfaces to support the modular interconnection of the steering arm and the drive unit, Fig 2.18 c. The front and bottom plate of the drive unit attaches to the vertical and top plate of the steered pivot module, Fig. 2.18d. The final product is a modular vehicle corner unit, wheel robot, which connects the drive unit to the chassis, Fig 2.18 e.

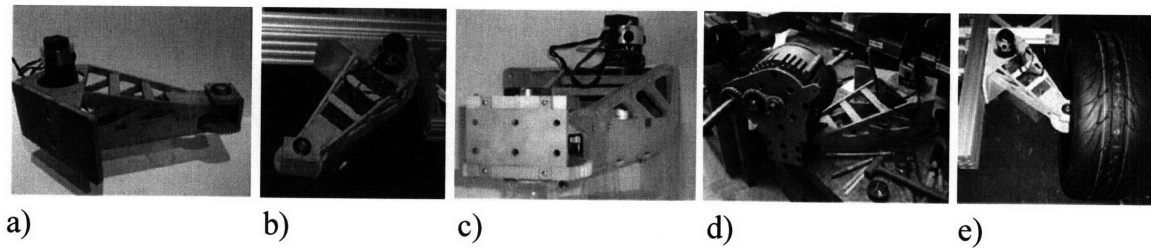


Fig. 2.18 4-Wheeler Side Steered Modular Wheel-Robot

2.5 Active and Split-Active Caster Wheel-Robot Scaled Prototypes

In an effort to understand the effects of omni-directional motion in physical space, a 1/8 scale mini Zero-Car vehicle was built based on the wheel base and track of the unfolded City Car platform. This scaled working prototype, the Mini-Zero, implements four drive wheels enabled with 180 degrees of overhead caster steering, Fig. 2.19 a. The overhead casters are actuated by four 1/4 scale R/C servo position motors that are mounted to the four corners of the laser cut acrylic chassis. The central vehicle computer – a stack of the following microprocessor modules: gum-stix, robo-stix, and wifi-stix – is mounted on top of the chassis along side its power supply of eight AAA batteries, Fig 2.19 b.

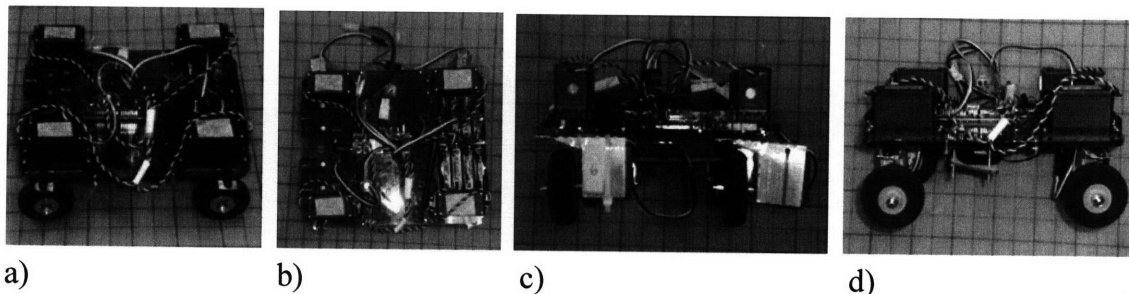


Fig. 2.19 “Mini-Zero” 4 Wheel Overhead Caster Omni-Robot (1/8 scale)

On the underside of the chassis are the servo drive motors and their 7.2V battery supply, Fig 2.19 c. Minus the actuator battery pack, the Mini-Zero is designed such that all of the

moving components are located in the underbelly of vehicle while the top deck reserved for the delicate electronics and wiring, Fig. 2.19 d. Communicating with an off board computer via a WiFi link, the Mini-Zero successfully executes both omni-directional translation and rotation maneuvers controlled from a wireless joystick input.

The success of the Mini-Zero as a first attempt to understand omni-directional motion led to the fabrication of a number of 1/4 scale active caster omni-robot for future research in vehicle controls and automation. A four wheel omni-robot was built using the same principles of the Mini-Zero scaled by two, Fig. 2.20. This active caster robot demonstrated a large degree of omni-directional motion yet it was constrained to maneuvers that could be made with 180 degrees of steering travel, due to the mechanical limitation of the servo steering motors. Also the robo-stix motor controller have six servo outputs available, while the four wheel omni-robot uses eight actuators, which meant that 2 pair of actuators must share the same PWM output control signal.

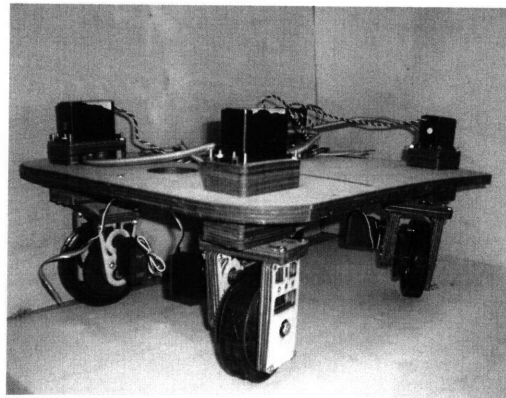


Fig. 2.20 Omni-Robot, 4 Active Casters

In order to better match the actuator output control capabilities of the available gum-stix CVC, a set of equilateral omni-robots were designed and built with two different wheel-robot technologies, the active caster and the split-active caster. A new split-active caster wheel-robot was designed with the dual servo drive motors, a dedicated optical encoder per wheel to measure wheel rotation, and a free rotating hollow steering shaft, Fig. 2.21.

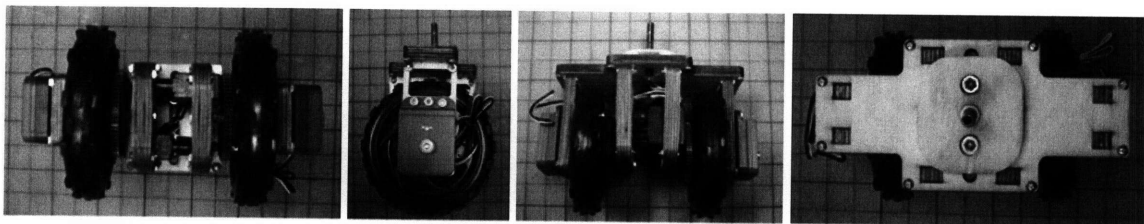


Fig. 2.21 1/4 Scale Split Active-Caster Wheel-Robot

Three split-active caster wheel-robots were mounted to triangular chassis such that they freely rotated with out mechanical interference, Fig. 2.22 a. A set of three optical encoders were individually mounted to the steering shafts of the split-active wheel-robots

in order to measure the steering angle of their rotation, Fig. 2.22 b. Similarly, three 1/4 scale active caster wheel-robots were mounted to a separate equilateral chassis making sure to avoid mechanical interferences, Fig. 2.22 c. Their steering shafts were attached to a set wench servo motors with 1080 degrees of rotation, Fig. 2.22 d. Each three-wheel omni-robot demonstrates full omni-directional motion.

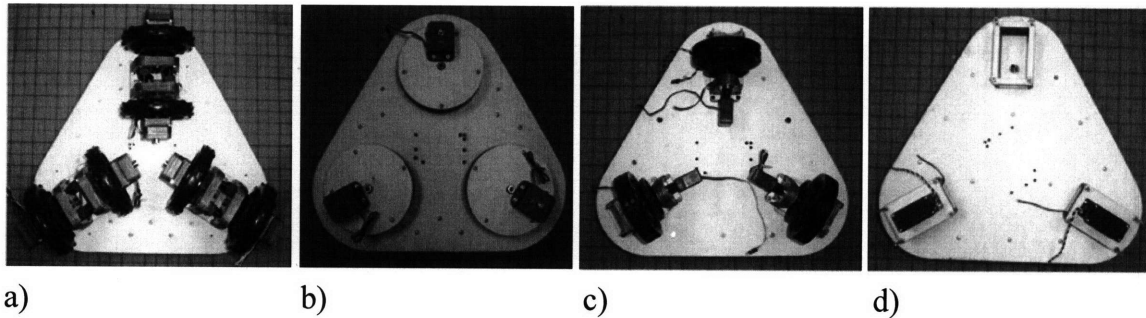


Fig. 2.22 Top and Bottom View of Equilateral Omni-Robots

The physical models created for the split-active offset caster wheel robot, the two active caster omni-robots, the split-active caster omni-robot and a number of the omni-directional vehicle sketch models all use a multi-layer fabrication process to rapid prototype 3-D objects out of 2-D parts. A 100 watt laser cutter, from Universal Laser System of Scottsdale, Arizona, was utilized to cut the 2-D parts out of three-ply birch lanan, in both 5 mm and 10 mm thicknesses. Birch plywood, was the material chosen for rapid prototyping physical models because of its electrical insulating properties, for ease of manufacturing, and as an ecological alternative to acrylic and other plastics. Parts fabricated with the laser cutter are constrained to fit on the 18" x 32" cutting bed. Thus pieces larger than the limits of the bed must be designed such that the partitioned pieces can be reassembled with structural integrity as the highest priority.

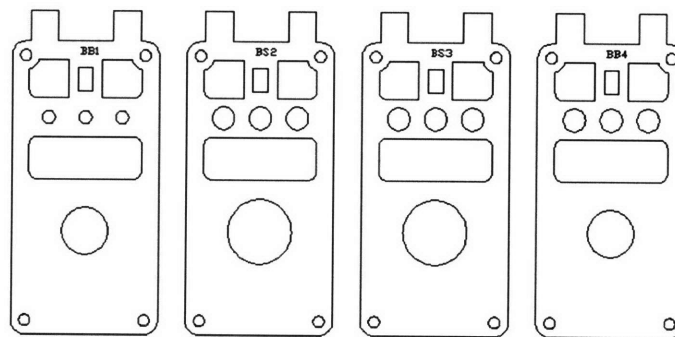


Fig. 2.23 2-D Cut File for a 3-D Plywood Lay-Up

An example of the multilayer fabrication is illustrated in the image captured below . These from Auto CAD below. which shows the 2-D elevation view of 4 pieces to be cut and layered on top of each other. Starting form left to right such that, the pieces will be layered on top of each other with the middle two pieces holding a roller blade bearing, to create the bearing block for the active caster wheel robot that allows for an optical

encoder to be mounted to its side. BB1 is layered on top of BB2, on top of BB3 on top of BB4. It part is labeled with a letter number combination as identifier for assembly purposes. In the case below, BB stands for Bearing Block, and the number is designated for order of assembly.

A major portion of the rapid prototyping process is the use of computer aided design, CAD. For this thesis, software packages such as Auto CAD 2005, CATIA V5, Rhino 9, and 3ds Max 9 were used to design render and fabricate the physical and digital models. As a way to simplify the design process, a number of parts were used repetitively during rapid prototyping. Some of the parts used repeatedly include 608ZZ skateboard roller bearings, from VBX, the Vex robotic kit components, which include the continuous variable servo motor, 100 division rotary optical encoder, 12 and 60 tooth gear sets, 1/4" square axels, 4" & 5" wheels, the Hitec HS-785HB winch servo motor and a number of fasteners that were limited to three types, size 6-32, 8-32, and 5/16-18.

2.6 Omni-Directional Vehicle Control Algorithms

To control the active caster and split-active caster robots, a floating point in 2-D space is used to rotate the robots about. In rotation mode, the wheels of the robot are constrained to be tangent to a circle created by the radial distance between the floating point of turning and the pivot point of the wheel, Fig. 2.24a-c. In translation mode the wheels are constrained to being parallel to each other at all times.

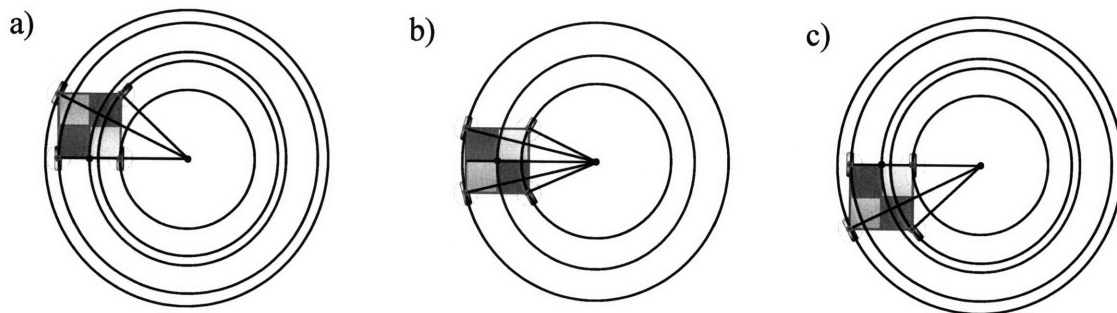


Fig. 2.24 Steering Geometry for Control Algorithm: a) Front, b) Center, c) Rear

The algorithm will also have a mode for normal steering, that is a subset of rotational steering, with limited steering in the front and the rear by moving the point of steering into the body of the car, such that the front or back wheels are not effected by the floating turning point, and such that the steering node moves along the center line of the vehicle, Fig. 2.25.

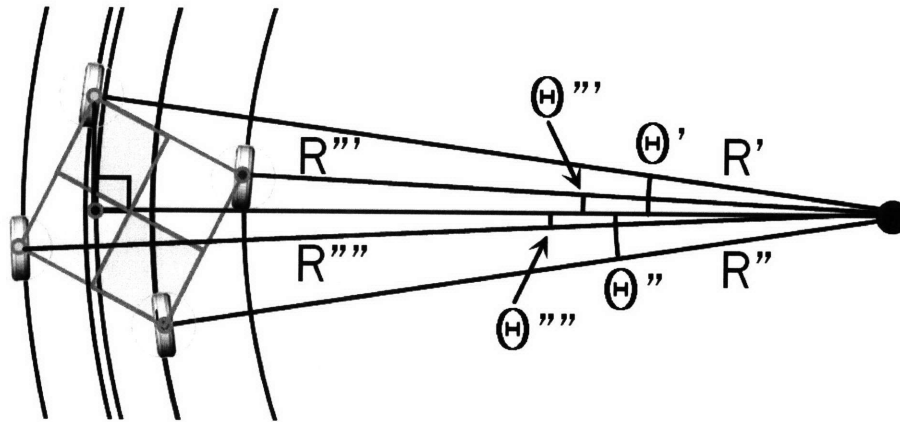


Fig. 2.25 Steering Geometry for Control Algorithm: Blue Geometry, Floating point and Reference Lines.

The final mode of control will be a combination of rotation and translation, where each wheel has its own node to rotate about such that the resultant motion is both a rotation and translation, Fig. 2.26.

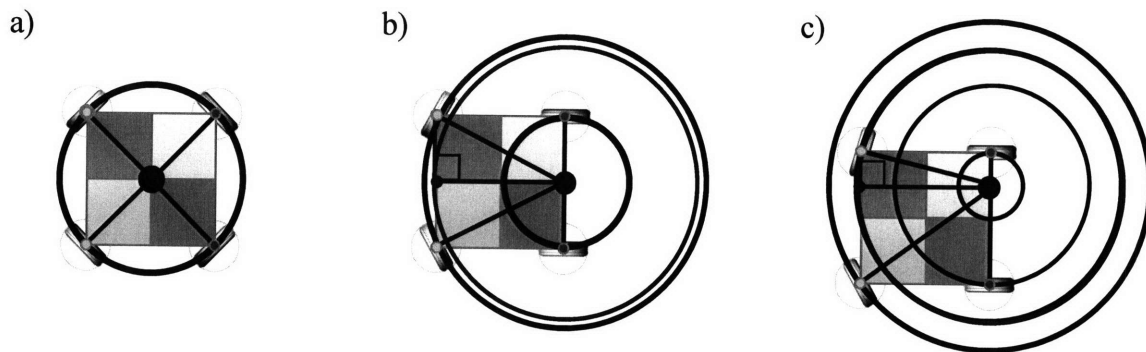


Fig. 2.26 Steering Geometry: a) Floating Point and Turning Point at Vehicle Center, b) Turning Point Centered Along Right Vehicle Edge, c) Turning Point Offset Along Right Vehicle Edge.

3 Vehicle Prototypes and Proof of Concept

3.1 Omni-Directional: Scooter, Automobile, Bus

The technologies of omni-directional mobility can be applied to a range of city-scale vehicle solutions. In addition to a fully omni-capable city bus, a mobility scooter and automobile designs have been developed. The prototypes are intended to show the flexibility of omni-directional mobility solutions, and potential applications of a universal wheel technology. Caster based steering can be integrated into various forms of existing human transport, including a mobility scooter. Traditionally used for the disabled and handicapped, this design strives to provide an alternate means of individual transportation to bipedal locomotion. The omni-directional mobility scooter can best be described as

surrogate legs while, perhaps on more amenable terrain, it may be far superior to legs. Among the many novel traits of the mobility scooter is the ability to articulate into different configurations, ride positions and heights, although this is not available dynamically. An intended use of the variable ride heights and configurations is to overcome the height difference between riders and upright pedestrians. The attention paid to facilitating eye-level interactions is relevant to improving city interaction across all new mobility devices. In the case of the scooter, an ideal option would be to allow for upright seating and a crouched position at speed.

These three vehicle designs are intended to show both the versatility of the technology, but also how they can form the first elements of a cast of vehicles that work in conjunction and may seamlessly share travelling space. The mobility scooter envisioned would span the range of personal mobility needs with the freedom to travel at speeds of 100km/h, and the ability to use the same device indoors at low speeds. This would require addressing the disparate dynamics and stability issues for such a range of speeds. Additionally, the scooter should be able to turn on its own foot print, adjust ride height at different speeds, use the split active caster in the design and exploit the possibilities that come from omni-directional motion. The initial design proposal is a three-wheel scooter – Fig. 3.1 – although a range of solutions, from a single split-active Segway design to four split-active caster wheels, have been considered. The scooter may fold to save space or to adjust ride height to increase omni-directional mobility and visibility at low speeds.

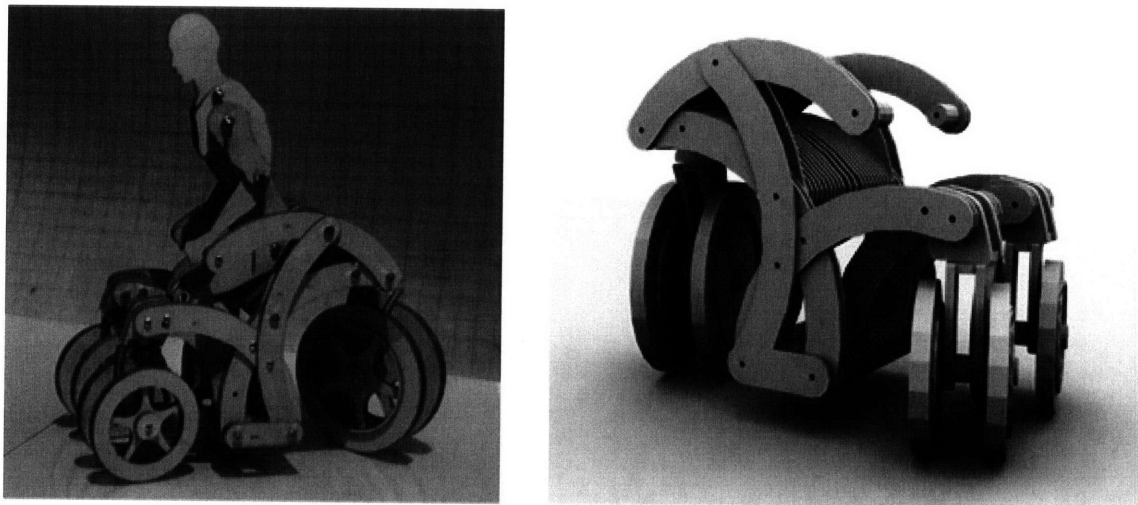


Fig. 3.1 Omni-Directional Mobility Scooter ¼ Scale Laser Cut Model

Mobility scooters might change the perception of road-going vehicles, but they should also bridge a gap in personal mobility. They should not require, but may motivate the creation of scooter lanes. More importantly, they could redefine and meet the need for a new entry-level vehicle.



Fig. 3.2 Tarantula Omni-Directional Mobility Scooter

The omni-car will depart from the sedate city car that is known today and look for an aggressive stance that accentuates the abilities of omni-directional motion and the technology behind the overhead split-active caster, Fig. 3.3.

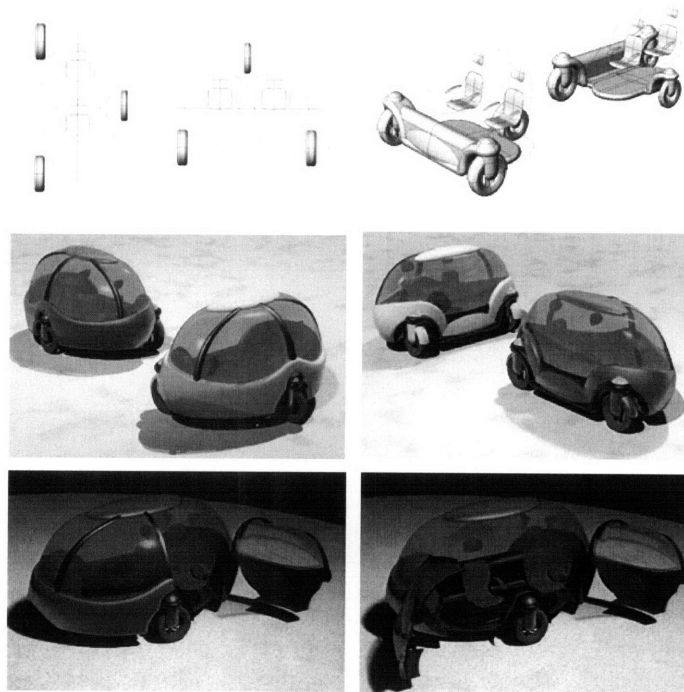


Fig. 3.3 Omni-Directional Cars Active Caster Car, 3 Wheels

The design should also accent the overhead split-active caster technology with a possible change in rake, Fig. 3.4.

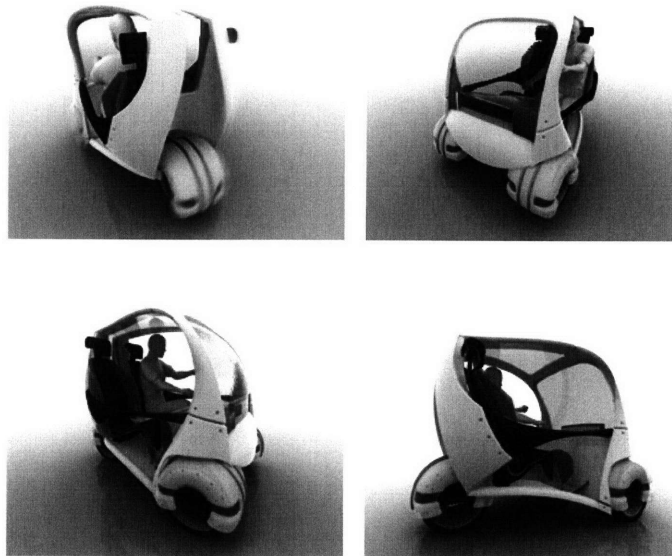


Fig. 3.4 Omni-Directional Car Split-Active Caster Car, 3 Wheels

The omni-directional bus is also designed around the split-active caster technology, and will meet the needs and capacity of the traditional bus, but address the issues of omni-directional motion in a rectilinear city. The bus will be the length of a traditional bus but use an arrangement of multiple split-active casters placed strategically along the length of the bus, Fig. 3.5.

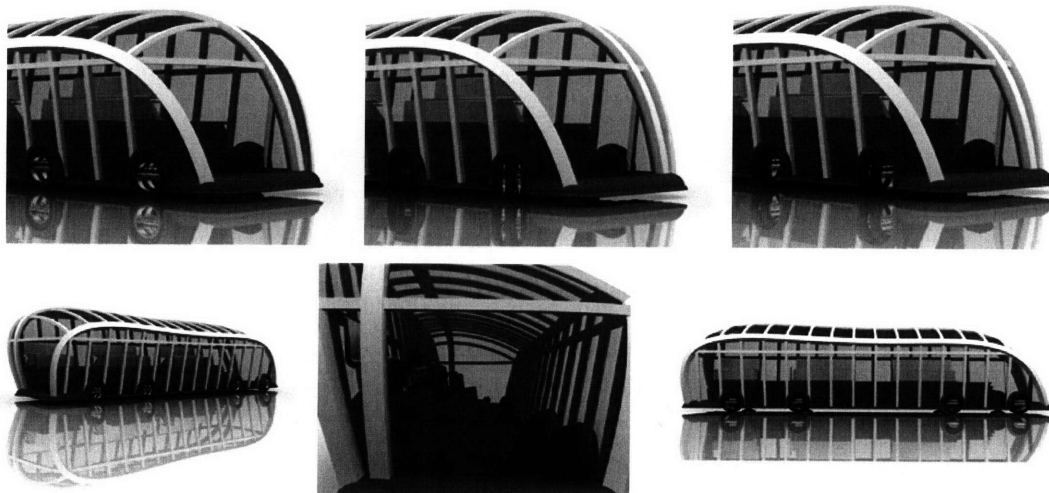


Fig. 3.5 Omni-Caster Lattice Bus

Taking advantage of the skateboard-type platform made possible by the wheel robot drive train, the bus can feature increased visibility using a lattice safety structure and a full-length safety glass greenhouse and side curtain. This visibility will allow the operator to more safely execute omni-directional maneuvers. The added visibility will also allow riders to enjoy a fresh look at the city while experiencing new driving paths utilized by the bus. To maintain visibility and benefit ingress and egress, stadium-style seating configurations will be considered, preserving the passenger's experience as a spectator.

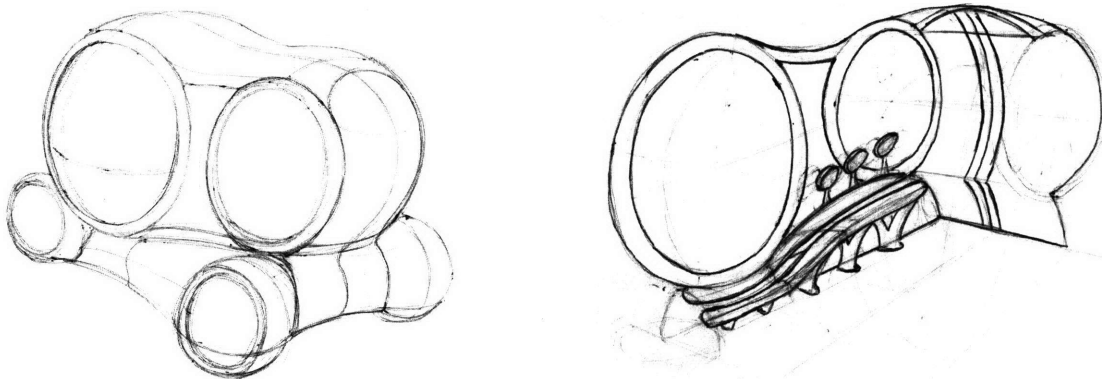


Fig. 3.6 Omni-Directional Shuttle Bus with 4 SAC

A second, smaller shuttle bus may be designed to carry 16 passengers, using the split active caster technology and the potential for fully omni-directional motion. The Omni-shuttles will also utilize a full length green house and glass side curtains, Fig. 3.6. The design will also address the flow of people through the interior.

3.2 RoboScooter

The RoboScooter is a built prototype aimed at providing an inexpensive, personal transportation option for urban areas, all while eschewing the typical costs and externalities associated with independent mobility, such as limited road and parking space, environmental emissions and energy use.



Fig. 3.7 RoboScooter Profile of Aluminum Frame and Electric Wheel-Robots

Ideal for urban settings, the RoboScooter's lightweight chassis and battery-powered electric motors produce zero nocturnal or tailpipe emissions, little noise and little environmental impact. The scooter also folds for space-saving parking, further decreasing its ecological or asphalt footprint, as less paved urban space is demanded. And it allows a transition to the scooters where space is at a premium, or parking cannot be expanded. Correspondingly, scooter racks with integrated charging stations have been designed which can be installed throughout a city, compensating for and enabling the use of short-range, lighter, and thus energy-saving battery packs.

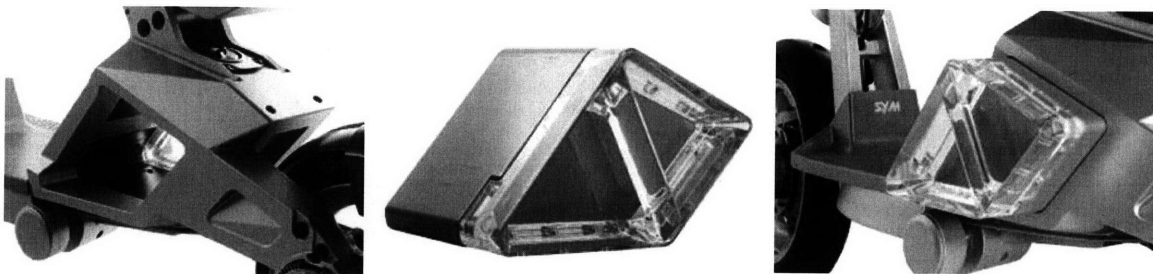


Fig. 3.8 Easy Exchange Battery Pack

City-wide installation of scooter racks also fits into a model that minimizes user decision-making and, unlike other vehicle-sharing arrangements, carries no need to refill a gas tank or find a power source other than returning it to a rack. In addition, battery packs have been designed to be accessible and exchangeable in case of battery failure. This enables quick turnover if another scooter is not available or an independent market for renting or exchange of batteries in an area that has not committed to installing charging stations. Alternately, convenience stores could maintain a stack in case a battery has lost all charge while not in the vicinity of a charging station. All of these arrangements could also enable a one-way rental model, much like the large-scale one-way bicycle rental

system recently implemented in Paris. Such a system could be integrated with a transit system very effectively by locating charging stations in high-density commuter transfer points, like transit stops.

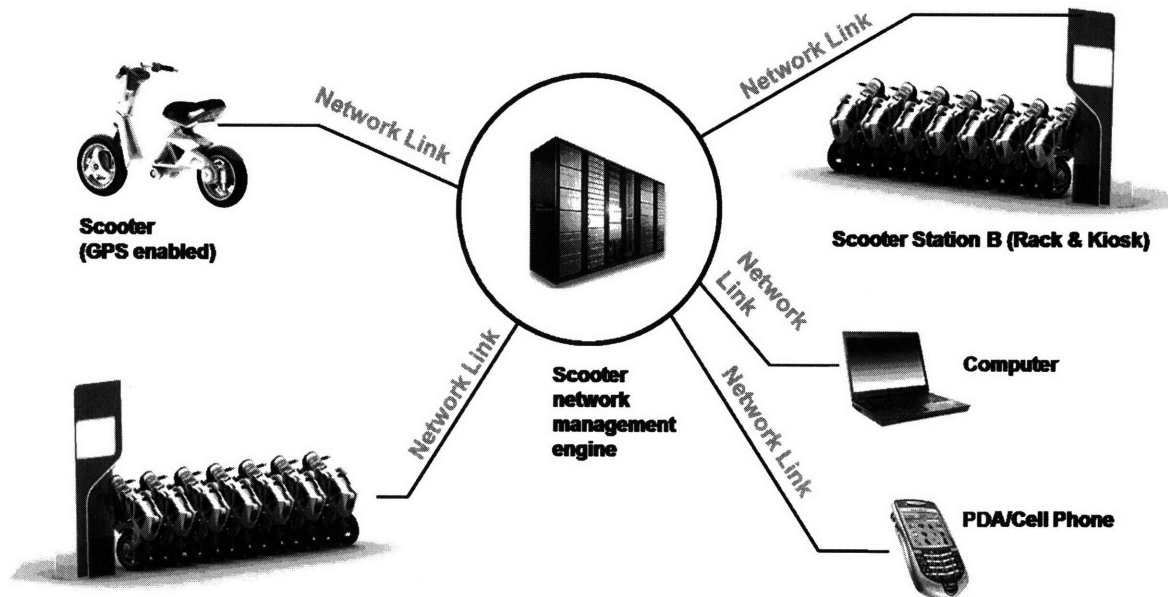


Fig. 3.9 RoboScooter Shared Use Network

Using the robot wheel technology also allows the development of two-wheel drive scooters without the complications encountered with standard drive trains. The robot wheels also allow the folding which reduces the space footprint by half.



Fig 3.10 RoboScooter Folding Sequence

A central pivot, similar to what may be seen in other robot wheel enabled mobility scooters, allows the wheels to fold out of alignment. In this position it is approximately the size of a rolling suitcase and can supply a power assist for easier transportation while maintaining the compact form.



Fig. 3.11 RoboScooter On Board Intelligence

The RoboScooter's building materials and structural components meld stability, utility and aesthetics. The lightweight exposed aluminum frame is minimally covered in body panels and, along with the robot wheels, keeps the overall number of components to a minimum. The minimal mechanical and structural components are complemented by maximal digital technology including the robot wheel controls, integrated GPS navigation and displays. Finally, these technologies allow for an uncluttered, intuitive interface while applying intelligent drive control and energy management.

3.3 Full Scale 4-Wheeler

The 4-Wheeler is the Smart Cities first full scale prototype of the City Car. The vehicle is a platform for future research exploration of the wheel-robot technology, modular connections, driver interface, control systems, sensor technology and battery management. Early studies debated the tradeoffs of the over head caster and the side steered wheel-robot strategies for omni-directional motion.

The proposed overhead caster chassis has a symmetric foot print with the passenger seats offset to the rear half of the vehicle, Fig. 3.12 a. The placement of the steering towers is pushed towards the corners of the vehicle allowing for egress through the front and sides

of the vehicle, Fig. 3.12 b. A wrap around user controlled joystick is provided to both occupants of the vehicles, Fig. 3.12 c. It was reasoned that the fabrication of the overhead caster strategy had complexities with the rigidity of the steering arm, the need for a slip-ring to transfer power and data across the pivot joint, and an additional volume allocation for the steering buttress. Thus the Smart Cities group decided to pursue the side steered 4-wheeler deal with these additional complexities straight out the gate.

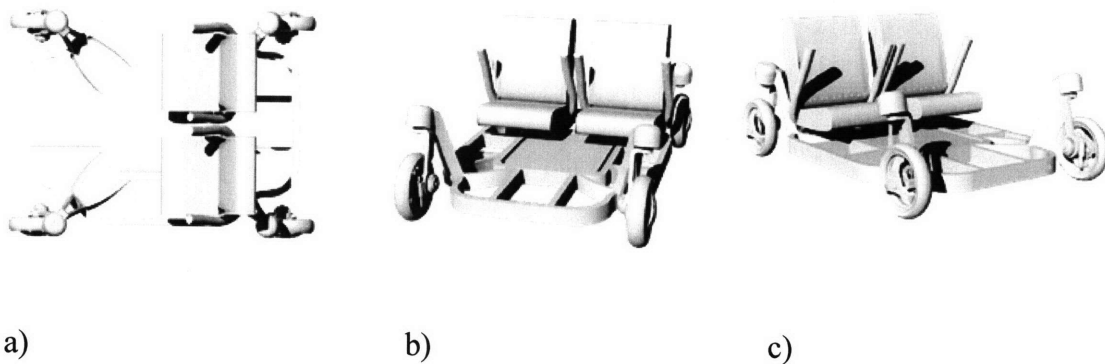


Fig. 3.12 Proposed Overhead Caster 4-Wheeler Design Strategy

The side steered 4-Wheeler is designed to place all of the steering components in the arm that extend horizontally from the chassis to the wheel-robot steering pivot, Fig. 3.13 a. This eliminates the need for a vertical overhead caster steering tower which lowers the vehicle's center of gravity, increases the available cabin volume while maximizing visibility, Fig. 3.13b.

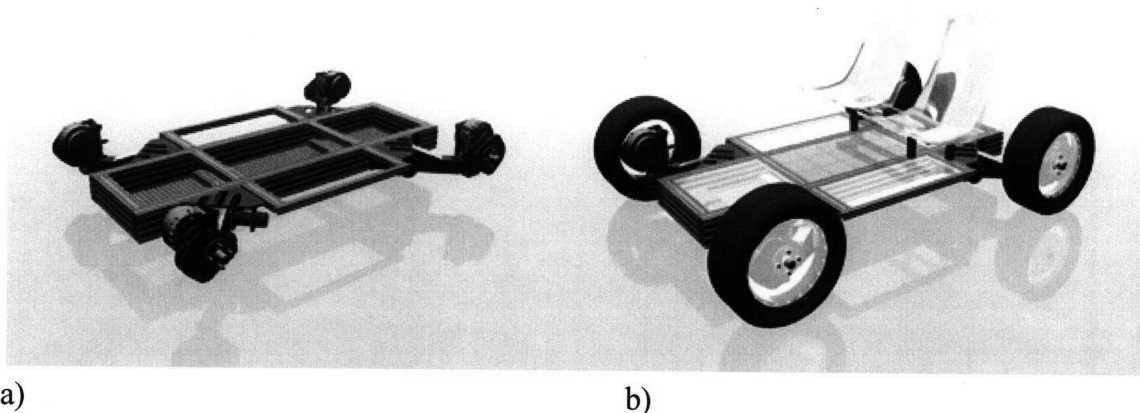


Fig. 3.13 Side Steered 4-Wheeler Chassis and Assembled Vehicle

The Side Steered 4-Wheeler is allows for 120+ degrees of steering which allows for multi-directional maneuvers. The side steered vehicle is able to turn on its own footprint

creating an O-Turn, Fig. 3.14 a. Within the 120 degrees of rotational steering, the vehicle can also turn all of its wheels 90 degrees from the traditional automobile alignment to perform a perpendicular translation, Fig. 3.14 b.

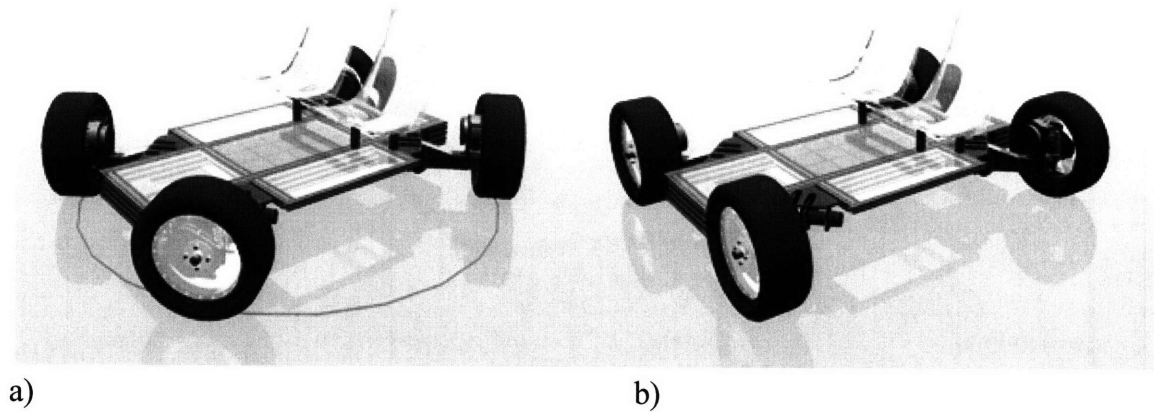


Fig. 3.14 Side Steered 4-Wheeler Chassis O-Turn and Perpendicular Translation

To expedite the fabrication of the side steered 4-Wheeler, the group order a number of off the shelf components for power and actuation. The key components include the Mars 48V-100A BLCD drive motor, the Kelly Controls 48V-200A BLDC motor controller, the RoboteQ AX3500 24VDC-60A brush steering motor controller, the Magmotor S28-400X, 24VDC- 200A steering motor, and the Thunder Sky 3.2V-40Ah Lithium Iron Phosphate battery cells, Fig. 3.15.

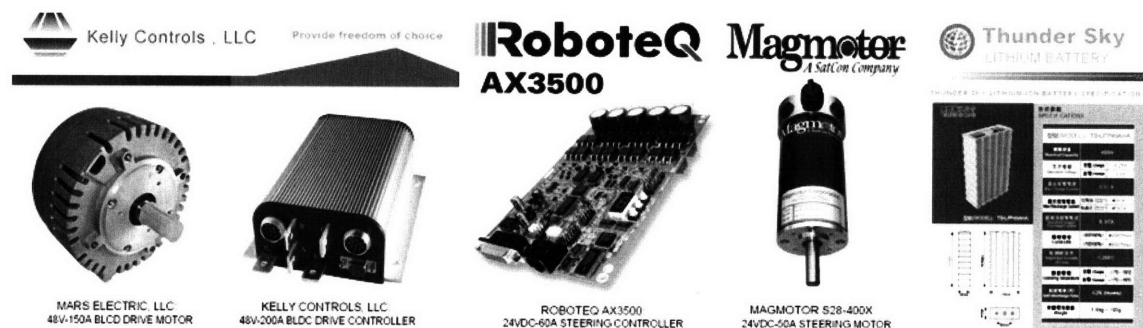


Fig. 3.15 4-Wheeler Key Actuation and Power Components

These components are integrated into the side steer wheel-robot modules and are mounted onto the 80/20 aluminum extrusion chassis, Fig. 3.16 a. Eight Thunder Sky battery cells are wired in series to create three 24V battery packs. Two of these packs are then wired in series to make one 48V battery pack, and one 24V battery pack which are stored in the center of the chassis Fig. 3.16 b. The control components are wired, programmed and placed in the front and rear bay of the chassis, Fig. 3.16 c.

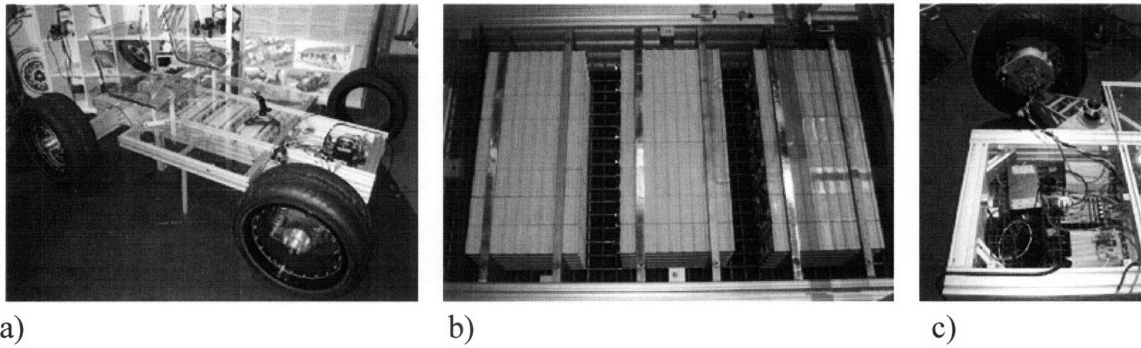


Fig. 3.16 Assembled Side Steered Prototype with Component Integration

The 4-Wheeler is currently half complete and research on this project will continue over the summer of 2008.

4 City Scale Implementation

4.1 Mobile Omni-Directional Interaction

Navigation in the city is primarily done in a rectilinear fashion, as evidenced by the common grid layout of urban roads and buildings. Factors that likely contributed to this nature are the simple division of land, linear construction of buildings, and ease of navigation. Rectilinear design also has a self-propagating tendency, with building materials, transportation solutions and further city development often conforming to the design in place.

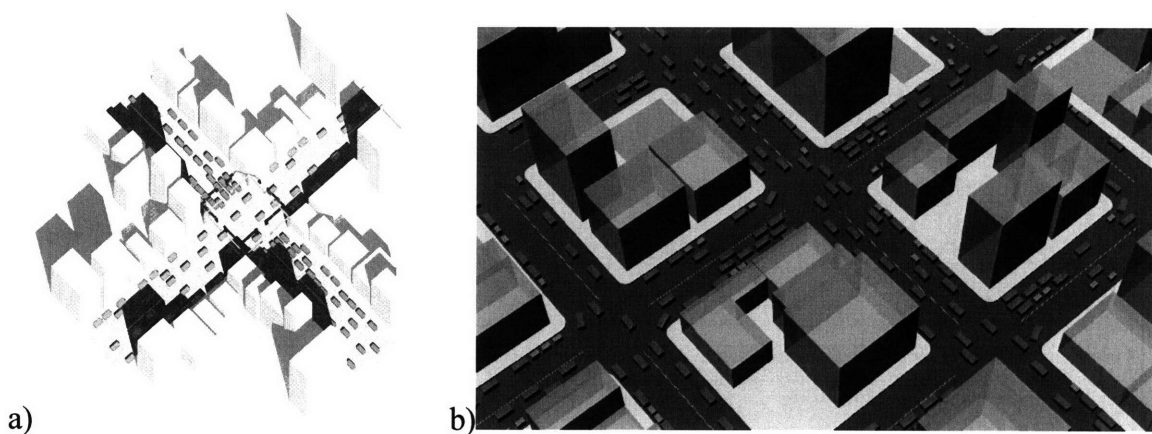


Fig. 4.1 a) Rectilinear intersection, b) Resultant grid city.

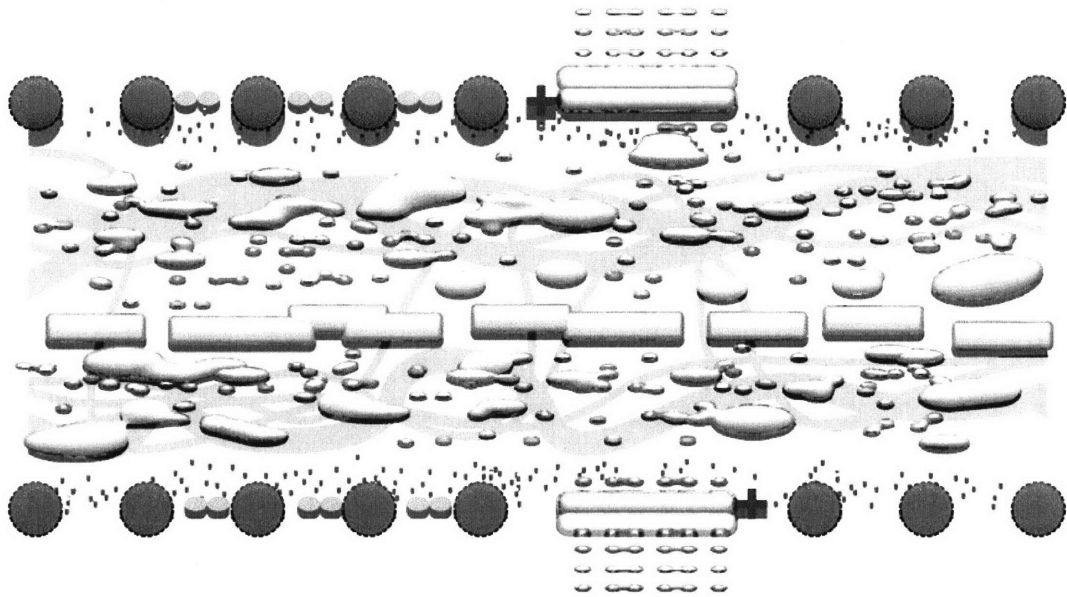


Fig. 4.2 Freeform City Developed Inside Rectilinear Vestiges.

Excessive regularity without landmarks or other recognizable interruptions can be disorienting because of a lack of differentiation. As long as a mental map can be formed to create a sense of legibility, the city could utilize more free form design and take advantage of omni-directional transportation solutions. Thus Fig. 4.2 may develop from the cruciform depicted in Fig. 4.1. The advent of GPS and CAD tools already aid the integration of curved shapes and borders into city design.



Fig. 4.3 Complex Articulated Omni-Vehicle that can be Fabricated with CAD

The rectilinear grid is also less crucial for route planning with intelligent navigation systems aided by GPS. These tools also allow people to safely explore or get lost in new parts of the city that they might not otherwise experience. Omni-directional transportation can aid in this ability to investigate the city in new ways. These changes, aided by omni-directional motion, can also allow the city to follow new growth paths and to develop new patterns of activity, which may be more amenable to a dynamic urban environment.

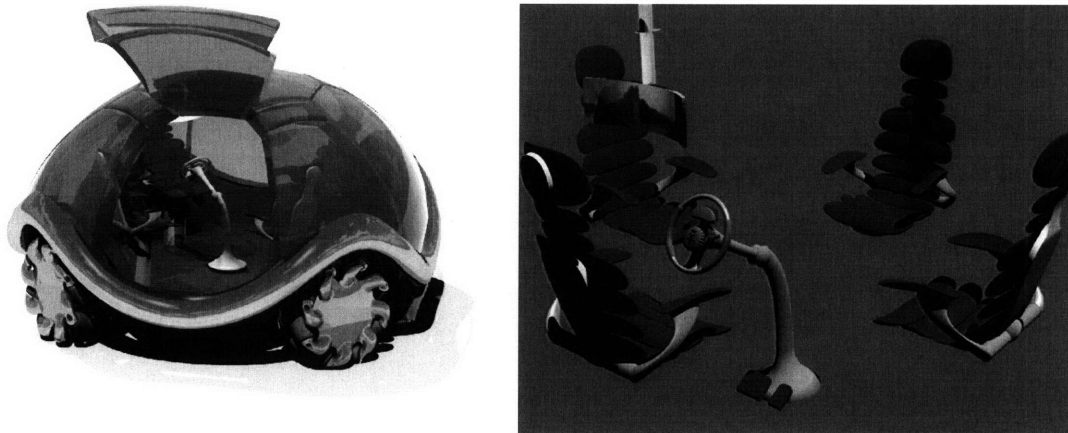


Fig. 4.4 Slow Moving Omni-Vehicle Social Seating and City Viewing Canopy

When traversing conventional or novel urban landscapes omni-directional vehicles will necessitate and enable new traffic control systems. These systems may be able to more efficiently allocate road space to omni-directional vehicles. Inter- or intra-vehicle communication and some global control could also increase the traffic bandwidth of current and future roads.

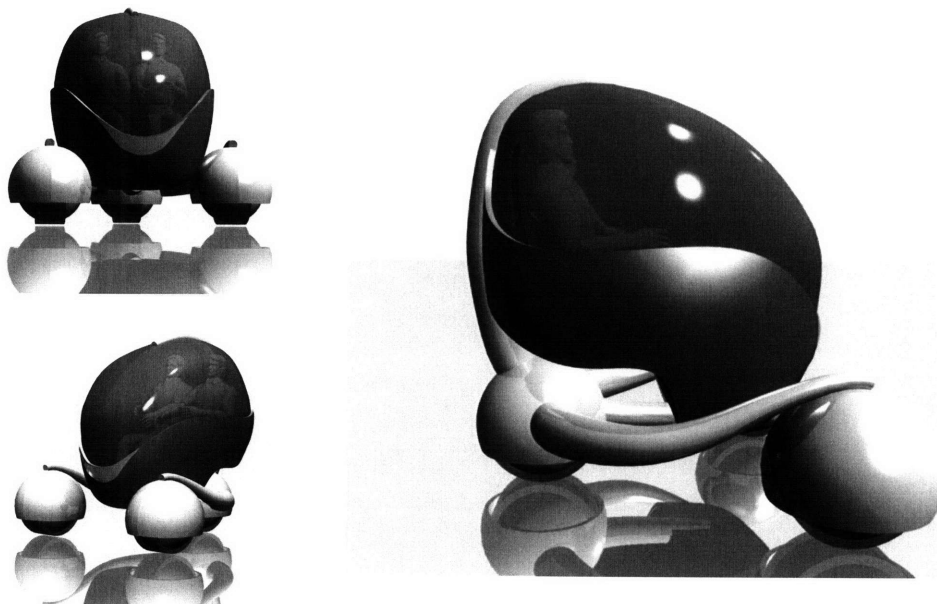


Fig. 4.5 Omni Vehicle for Omni-Flow through the City

The benefits of omni-directional motion to sustainable mobility are manifold. With greater maneuverability, vehicles can take smaller roads and more direct paths, which while slower, are more energy efficient. Larger vehicles with omni-directional capabilities, like buses, which carry more passengers per vehicle, can also navigate narrower streets reducing the demand for higher capacity highways which utilize disproportionately larger quantities of land.

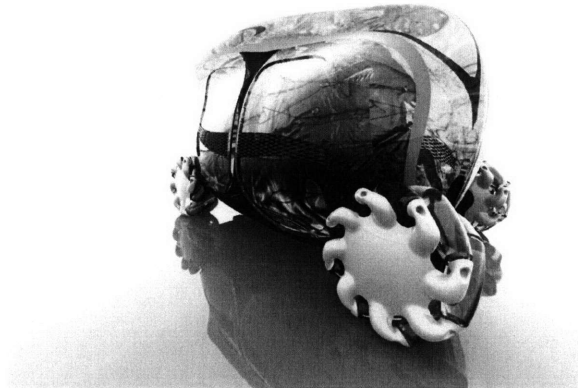


Fig. 4.6 High Occupancy Low Speed Omni-Vehicle

Whether parking a car, a scooter or pulling a bus into a loading and unloading zone, omni-directional vehicles would require less road space to maneuver into parking spaces, requiring less road space. Mobility scooters, able to make more abrupt maneuvers could be more compatible in mixed traffic situations with bicycles and pedestrians.

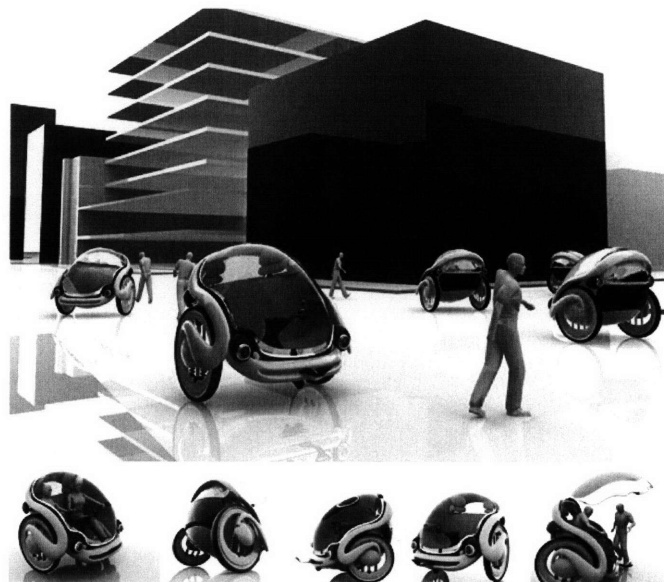


Fig. 4.7 Slow Speed Mixed Use Omni-City

Thus, many of the benefits improve the bandwidth of current roads, and could lead to more efficient land use. The efficient use of land is crucial in sustainable development, especially given concerns of global climate change and habitat loss around urban environments.

4.2 Multi-Directional vs. Full Omni-Directional Motion

This thesis explores the promise of future mobility in the city, inviting a comparison of multi-directional and fully omni-directional motion in realizing the benefits of burgeoning technologies. One likely factor for any of the new technologies implementation would be the potential growth path. Many of the major benefits of omni-directional motion would only be fully realized in settings with widespread adoption. In today's primarily rectilinear cities, most traffic would not be compatible with fully omni-directional maneuvering. In part, because this fact is reinforced by the nature of the predominant vehicle types, a "shared space" area, where mixed modes of transportation share the same infrastructure, could be an ideal place to introduce omni-directional mobility.

Most of the motions commonly utilized in a city are covered by multi-directional motion technology that can rotate 120 degrees. However, the multi-directional vehicles must first come to a stop in order to utilize a translation or rotation, and then re-orient to the next move because of the limited steering angle. A holonomic system is one in which the degrees of freedom are equal to the number of coordinates needed to specify the configuration of the system. In the field of mobile robots, any mobile robot with three degrees of freedom of motion in the plane has become known as a holonomic mobile robot. (Holmberg, 1).

With an active caster wheel technology, the angle of wheel rotation must be unlimited to be considered fully omni-directional. Specifically, it must allow for $360 \times n$ degrees of rotation so that the same limitations are not encountered after one maneuver. Thus the full omni-directional vehicle must be free to rotate each wheel infinitely in any direction. This ability most closely emulates ambulatory behavior, and could thus potentially integrate with a mixed transportation environment.

4.3 Robot Wheel Communication

There are multiple ways for the robot wheels to communicate with one another. They can act as independent entities that communicate directly between wheels, or they can communicate through a centralized network. The communication must allow the wheels to be randomly placed anywhere on the structure, and the algorithms must be fault-tolerant and robustly adaptable to various configurations and wheel-replacement. A Gumstix, Robostix and WiFistix unit could be used for the centralized wheel robot network or one Robostix at each wheel in the distributed wheel robot system. While the Robostix module allows control for 6 output devices, the four-wheel vehicle uses two actuators per wheel robot for a total of 8 output devices. The six outputs are sufficient for

asynchronous translation and rotation using four outputs to control independent steering at each wheel, and the remaining two outputs split to control the front and back left-hand side drive actuators with one output and the right-hand side drive actuators with the other.

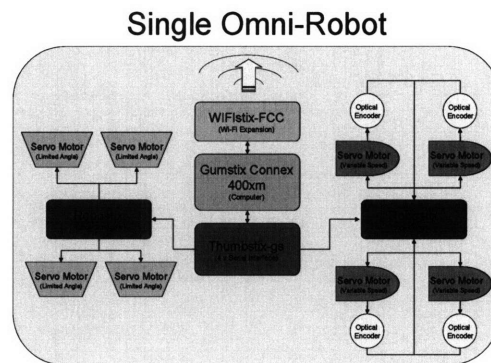


Fig. 4.8 Initial Wheel Robot Control Diagram Using Gumstix

The benefit of independent robots with one computer per wheel is that adjustments can be made independently from the mainframe, allowing for response to changing driving conditions on the fly and communicating its adjustments to other wheels so they may follow the lead robot wheel and adjust to its needs. It is possible to envision a number of intermediate solutions where each robot has computers that process the feedback loop of optical encoders and other inputs while a central CPU manages the network. Any design should allow for the ability to plug in a robot into any system such that the control interface is seamless.

4.4 Virtual Towing

There are multiple means of implementing virtual towing, including wheel-to-wheel communication, image recognition and global control. The first step to take advantage of the individual wheel robots is to follow a filmstrip approach where the motion of the wheel robots of the lead car are replicated by the wheel robots of the trailing car. An added layer of input could utilize distance sensing (e.g., optical or ultrasonic) to the edges of the lead vehicle and triangulate to determine the orientation and distance between cars. By incorporating varied tracking data, an eye in the sky solution might act as a redundant clearinghouse to check for self-consistency of spatial data like GPS and vehicle-based sensors.

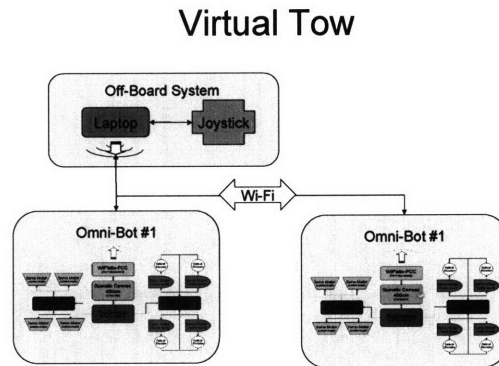


Figure 4.9 Virtual Tow Communication and Wheel Robot Control Diagram.

The current virtual-towing strategy is a simple system that communicates the relative position and angle of a lead vehicle to a platoon of trailing vehicles via an inter-vehicle communication network. The ultimate goal is for the platoon of trailing vehicle to traces the initial path traveled by the lead vehicle over an interval change in time. This is realized by tracking the lead vehicle's position and direction of motion to then be relayed to the trailing vehicles in the platoon, shown in Fig. 4.4 below.

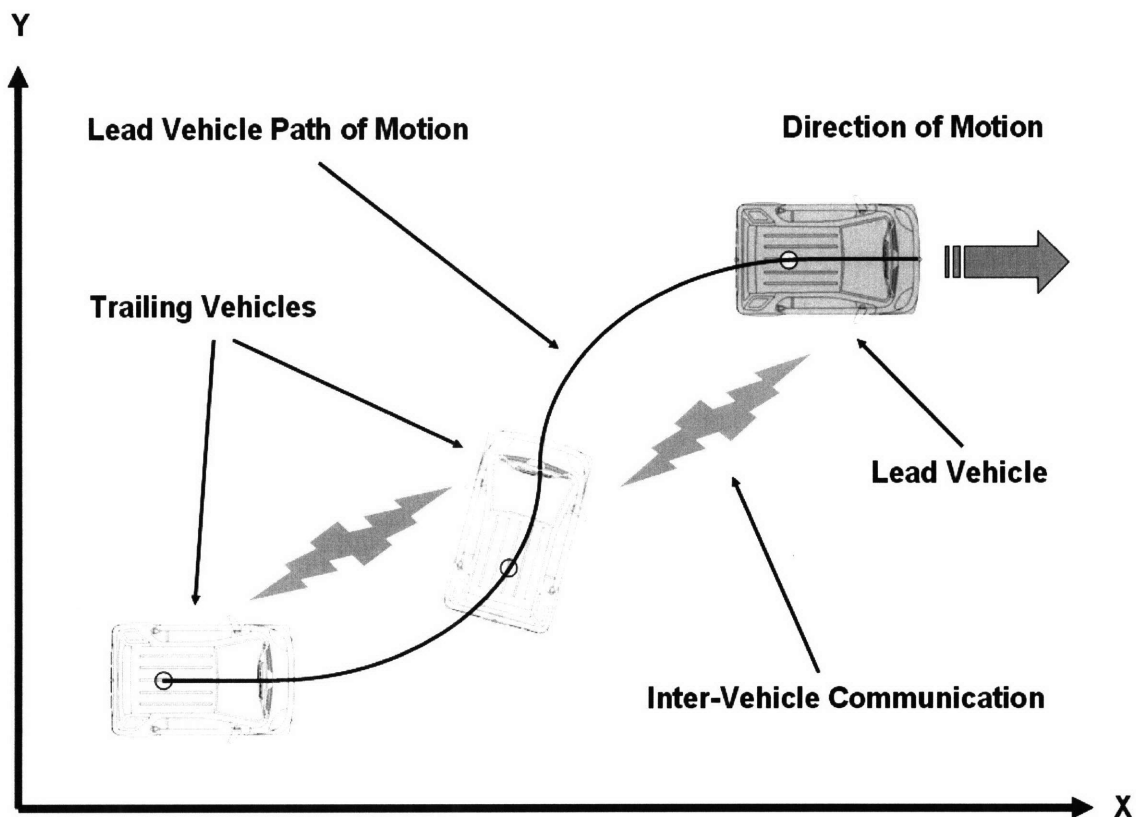


Fig. 4.10 Simple Virtual-Towing Strategy

An absolute coordinate system is used to monitor the position of each vehicle relative to the lead vehicle. The position and moving velocity of the lead vehicle is calculated using the network of optical encoders mounted to the drive shaft and steering axis of the individual wheel-robots. This information is transmitted to the immediate trailing vehicle then arranges the positional information and vehicle control volume of the lead vehicle received in time sequence and produces the trace line information of the lead vehicle. Further as the follow vehicle compares its own position and moving direction with the lead vehicle's trace line information, it is possible to estimate the current deviation from the targeted trace line of the lead vehicle.

4.5 Swarm Theory

The advent and potential omnipresence of omni-directional mobility would benefit from, as well as enable, further rethinking of city infrastructure and city-user interaction. Achieving the vision of a slower speed and more fluidly traversed cityscape would call for advanced routing, especially implementing the class of meta-heuristics based on swarm theory (ref. Rizzoli, et al)

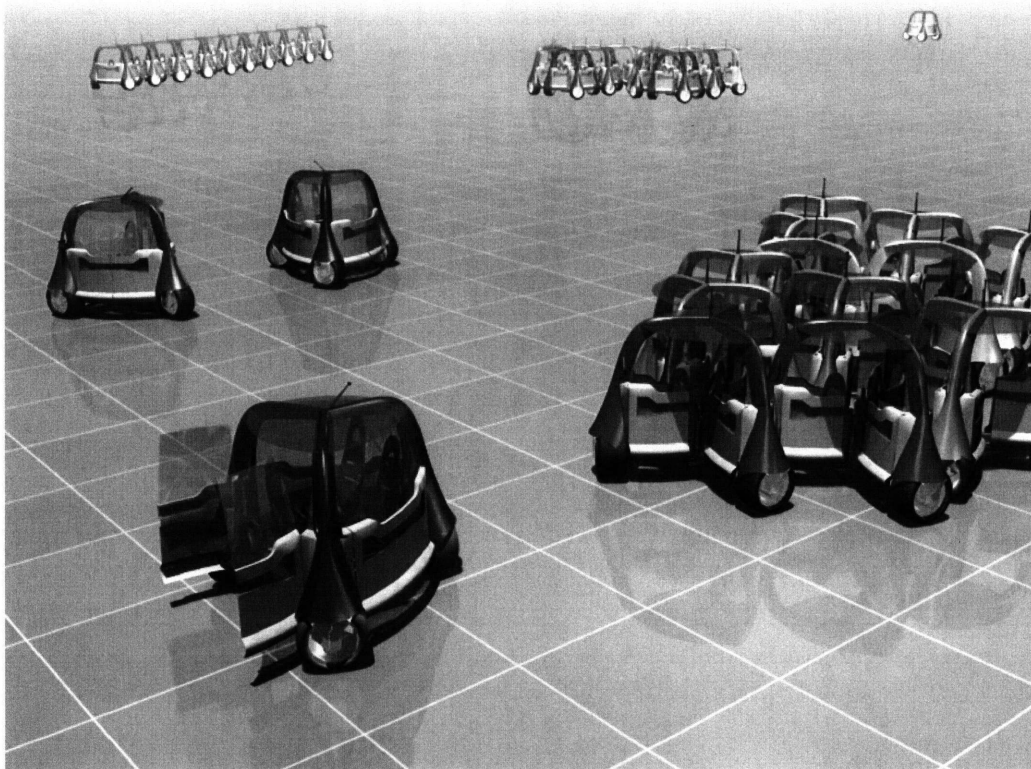


Fig. 4.11 Autonomous Omni-Directional Vehicles as Particles in Tow and Herds

Decision-making and routing heuristics inspired by animal behavior models can illuminate non- or even counter-intuitive solutions. In addition, they can be used with the hope of specifically mimicking and managing the results of these behaviors, like swarming and herding even in the absence of strictly defined lanes or other common traffic guides. Ant colonies, in specific, have been used to analyze logistics (ref. Rizzoli), traffic flow (ref. John, Schadschneider, et al) and path formation (ref. Nouyan, Campo, Dorigo) which could be applied to virtual towing. Defining a minimal radius for a distance of separation, rather than a generally linear distance shifts from strict definitions of lanes and lane-based maneuvers, such as standard lane changes, to a much more amorphous description of flow. Eventual implementations of such a concept would likely call for some measure of automated control and global exchange, if not computation of data. Omni-directional mobility allows the maneuverability in individual vehicles that can scale up to more closely mimic swarm and herd behavior. As a result, the technology may allow traffic flow that is ordered at a higher-level despite the apparent chaos of a looser set of rules, as seen in swarms and herds. As an example, the specter of traditional collision avoidance theory is broadened, especially when there does not have to be a singular response such as maximum braking from high-speed. Ideally, some mix of on-board and global automated control would enable such a change in rules.

Within the class of Vehicle Routing Problems (VRPs), dynamic vehicle routing attempts to optimize routing decisions based on changing constraints. Many of today's solutions are grounded in swarm theory, inspired by ant colony models. Omni-directional mobility, which can most closely mimic the actual range of motion seen in such insects, could allow for a much closer emulation of their physical behavior. These vehicles would sharpen the resolution of control, and as such, the scale at which individual agents can emulate the modeled motion. This sharpening of scale allows higher-order effects to be achieved at a smaller physical scale – creating a smaller ecological footprint. It also allows the vehicles to more seamlessly integrate with pedestrians in a “shared space” scenario. In addition, one can achieve a level of choice never attained in any form of human transportation short of bipedalism. Dynamic VRP could empower real interaction with the city by allowing occupants a fluid choice of destination in an automated driving scenario. The ability to observe and respond to one's settings, and in an energetically optimized manner, essentially gives the occupants the ability to “efficiently roam”. In this sense, omni-directional mobility and dynamic VRP solutions could shift transportation into a new paradigm where global-aided control empowers more choice.

4.6 Automated/Assisted Driving: Global vs. User Control

The freedoms associated with Omni-directional motion also push the limits of the driver control of a vehicle. Such a radically new driving scenario demands new levels of user control and awareness. The user that is accustomed to moving in a rectilinear manner can become disoriented while making omni-directional maneuvers at any speed. Individual control may not be as complicated as communication with other drivers, especially when unexpected maneuvers are executed. Reliable visual cues may not suffice and to ensure safety there may be a trade off between user control and global control of car movement.

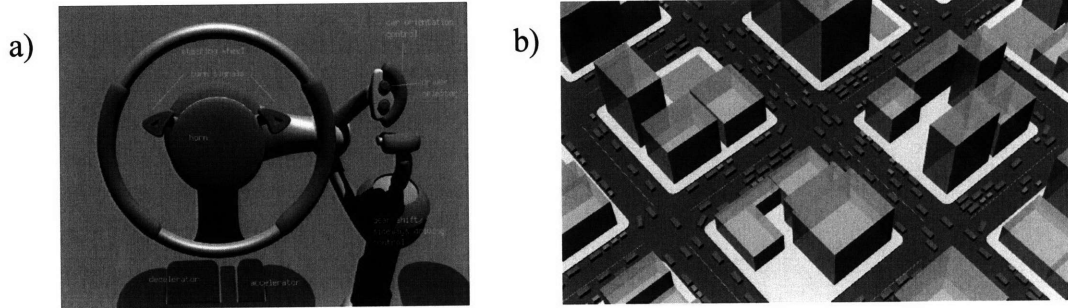


Fig. 4.12 Driver Control: a) Omni Steering Wheel and Joy Stick, b) Global View Urban Traffic.

The aim is to achieve a mix of the two in a system where there is global control of space within which a user has free reign to make maneuvers and travel in space and time. The controlled spaces can be defined spaces that allow for full omni-directional movement since there are no other users to travel in that space, or as more users travel in closer spaces it may be limited to requested movement. Omni-directional motion may be done with more user based control with limitations in the movement through intelligent proximity sensing but global control may more fully utilize omni-directional capabilities and dynamic vehicle routing.

5 Evaluation

In order to understand omni-directional motion in the city, this thesis has evaluated the design and implementation of both the active and split-active caster wheel robot by comparing each technology in multiple scaled physical models. The city-scale split-active caster technology was the basis for 3-D digital model designs of the omni-mobility scooter, omni-car, and omni-bus. The digital models have been placed in their respective urban contexts using animations and simulations to demonstrate their maneuverability, stability and usability with respect to their footprint geometries and the physical use constraints in the city. The omni-directional motion algorithms created for the quarter scale active and split-active caster omni-robots were evaluated for basic functionality. Further evaluation would compare run-times for various mixes of operations to create a metric for their efficiencies.

The design process revealed the complex troubleshooting necessary for a ground-up redesign of the wheel technology, but reinforced the need and viability of a universal, interchangeable wheel robot. The overhead caster example captured the difficulty in prototyping novel mechanical interfaces, but the fully built split-active wheel robot and related quarter scale robots demonstrate the viability of the interchangeable wheel robot scheme.

While the most thoroughly tested prototype was the RoboScooter, it incorporated many of the fundamental design elements that would be incorporated in the other vehicles.

Though it did not implement the omni-wheel technology, its use of a wheel robot and the nature of its proposed deployment lend credence to many of the concepts of the total vision.

6 Conclusion

Although not tested in a complete physical model, the concepts of applying omni-directional mobility in multiple, modular city-scale implementations still seems viable and potentially beneficial to the sustainable design principles laid out. The quarter scale active caster and split-active caster omni-robots should still be tested on a defined obstacle course with multiple surface changes, to determine the performance characteristics of each wheel robot design. Additionally, each individual quarter scale wheel robot will also be tested in stationary operations, looking for power consumption during steering, and the resultant force of scrubbing friction.

The virtual towing algorithm should also be tested using the record and play filmstrip strategy to demonstrate the follow the leader concept, recording the maneuvers of the first omni-robot to be played back by the second omni-robot over a hard obstacle course. The full-scale active and split-active caster wheel robot will be evaluated using the zero car platform to test the omni-directional maneuverability of each robot wheel by sending a common set of instructions to travel a defined path through a set of obstacle courses. The result from each comparison of the active and split-active wheel robot technology will be used to make a recommendation on which technology is best suited for city scale omni-directional mobility.

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9 Reader Biographies

Cynthia Breazeal directs the Lab's Robotic Life group and holds the LG Career Development chair, having previously been a postdoctoral associate at MIT's Artificial Intelligence (AI) Lab. Breazeal is particularly interested in developing creature-like technologies that exhibit social commonsense and engage people in familiar human terms. Kismet, her anthropomorphic robotic head, has been featured in international media and is the subject of her book *Designing Sociable Robots*, published by the MIT Press. She continues to develop anthropomorphic robots as part of her ongoing work of building artificial systems that learn from and interact with people in an intelligent, life-like, and sociable manner. Breazeal earned ScD and MS degrees at MIT in electrical engineering and computer science, and a BS in electrical and computer engineering from the University of California, Santa Barbara.

Chris Csikszentmihályi directs the Media Lab's Computing Culture group, which works to create unique media technologies for cultural applications. He has worked in the intersection of new technologies, media, and the arts for 13 years, lecturing, showing new media work, and presenting installations in both Europe and North America. He is a 2005 Rockefeller New Media Fellow, and recently finished a solo exhibition at the Location One Gallery in New York's Soho. Csikszentmihályi has taught at the University of California at San Diego, Rensselaer Polytechnic Institute, and at Turku University. He toured museums and nightclubs with his mechanical hip hop device, DJ I, Robot, which was nominated for the Best Artistic Software award at Berlin's Transmediale, while a previous piece, Natural Language Processor, was commissioned by the KIASMA Museum in Helsinki, Finland. The catalog for his installations *Skin and Control* is published by Charta and distributed by DAP, and he served on the National Academy of Science's IT and Creativity panel. Csikszentmihályi received an MFA from the University of California at San Diego, and a BFA from the School of the Art Institute of Chicago.

William J. Mitchell is director of the MIT Design Laboratory, holds the Alexander W. Dreyfoos, Jr. (1954) Professorship, and directs the Media Lab's Smart Cities research group. He was formerly dean of the School of Architecture and Planning and head of the Program in Media Arts and Sciences, both at MIT. Before coming to MIT, he was the Travelstead Professor of Architecture and director of the Master in Design Studies program at the Harvard Graduate School of Design; he has also served as head of the Architecture/Urban Design program at UCLA's Graduate School of Architecture and Urban Planning, and he has taught at Yale, Carnegie-Mellon, and Cambridge universities. Mitchell holds a BArch from the University of Melbourne, an MED from Yale University, and an MA from Cambridge. He is a Fellow of both the Royal Australian Institute of Architects and the American Academy of Arts and Sciences, and a recipient of honorary doctorates from the University of Melbourne and the New Jersey Institute of Technology. In 1997 he was awarded the annual Appreciation Prize of the Architectural Institute of Japan, and he is currently chair of the National Academies Committee on Information Technology and Creativity.

Mitchell's publications include: *Imagining MIT: Designing a Campus for the 21st Century* (2007), *Placing Words: Symbols, Space, and the City* (2005), *Me++: The Cyborg Self and the Networked City* (2003), *e-topia: Urban Life, Jim—But Not As We Know It* (1999); *High Technology and Low-Income Communities*, with Donald A. Schön and Bish Sanyal (1998); *City of Bits: Space, Place, and the Infobahn* (1995); *The Reconfigured Eye: Visual Truth in the Post-Photographic Era* (1992); and *The Logic of Architecture: Design, Computation, and Cognition* (1990).